The use of visual network scales in teacher leader development

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HIGHLIGHTS

- Teacher leadership activities can be organized around network concepts and images.
- Visual network scales are a pedagogical tool for presenting network principles.
- Networks move science teacher discussions toward broader leadership issues.
- Science teachers attach educational meanings to open and closed network structures.
- Teacher leaders benefit from hybrid networks with distinct open and closed structures.

ARTICLE INFO

ABSTRACT

Changes in the age and experience of the US teacher workforce have heightened the need for teacher leaders. Based on network-enhanced leadership development models advocated in the management sector, we developed an activity using Visual Network Scales as a pedagogical tool and assessed its utility within a teacher leader development program. Discourse analysis indicates teachers can discuss networks at both ends of a visual density scale, with discussions aligned to community-oriented leadership activities rather than personal classroom topics. Network analysis provides evidence for hybrid network structures explaining the diverse, concurrent set of local and regional activities ascribed to teacher leaders.

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1. Introduction

Over the last 20 years, pre-retirement turnover has resulted in the United States (US) science teacher workforce becoming both younger and older (Ingersoll & Merrill, 2010), as experienced mid-career teachers are replaced with younger (e.g., post-baccalaureates) or older (e.g., career-changers) novice teachers (Polizzi, Jaggernauth, Ray, Callahan, & Rushton, 2015; Rushton et al., 2017). The dwindling base of experienced teachers who remain are likely to face increasing pressure to provide the growing novice teacher population with support through mentoring, best practices, and community involvement (Rushton et al., 2014). However, with increased demand also comes an increased opportunity for experienced teachers to become teacher leaders that are capable of providing these supports.

Given the potential impact of teacher leaders, teacher leadership has become an area of intense interest in the international research and policy arenas (Brauckmann & Pashiardis, 2011). Although teacher leaders might traditionally be viewed as *leaders of teachers* (e.g. administrators), US scholars have advocated for a more robust understanding of *teacher leaders*, or teachers who maintain active teaching loads and lead from the classroom (Criswell, Rushton, McDonald, & Gul, 2018; Dozier, 2007; Katzenmeyer & Moller, 2009), consistent with the focus of this manuscript. Similarly, national efforts in the UK focused on "the capacity for teachers to exercise leadership for teaching and learning within and beyond the classroom" (pg. 963) (Muijs & Harris, 2006) rather than formal

roles of assistant head or subject coordinator. York-Barr and Duke's (2004) seminal review of teacher leadership literature from 1980 to 2004 focused on what established teacher leaders "do," such as mentoring other teachers and participating in professional organizations, but highlighted the process through which teacher leaders were developed was not well defined. A decade later, Wenner and Campbell's (2017) review of international teacher leadership efforts identified key aspects of teacher leadership to include leadership: (i) beyond their classroom walls, (ii) in professional learning settings at their schools, (iii) relevant to policy and/or decision making, and (iv) invested in improving student success at the school organization level. However, the reviewed leadership studies did not provide a consistent framework or grounding theory for developing teacher leaders.

Policy initiatives have begun to address this theory-practice gap by proposing different frameworks for teacher leadership development. For example, the National Board for Professional Teaching Standards has described a professional development or career progression that starts with pre-service teachers, and moves them through *self-focused* stages as novice, professional, and board certified teachers, before advancing to the *community-focused* stages of teacher leaders or leaders of teachers (NBPTS, 2016; Thorpe, 2014). In another example, the Noyce I-IMPACT project has proposed and refined the use of four metaphors for teacher leadership that also span self-focused and community-focused stages, and described activities to develop the metaphors (i.e. teacher as a fully functioning person, reflective practitioner, scholar, and learning partner) (Rushton & Criswell, 2015; Criswell et al., 2018; Alemdar, Cappelli, Criswell, & Rushton, 2018; Polizzi et al., 2018). Separately, the KyNT3 project has described six spheres of influence for teacher leaders, as well as vignettes for the core beliefs, dispositions, and knowledge/skills that can be cultivated to expand leadership capacity in each sphere (KyNT3, 2015). While frameworks may scaffold leadership activities in a sequence for logistical or credentialing purposes, a longitudinal analysis of teacher leadership development supports that leadership develops via more cyclical, overlapping, or dynamic interactions (Taylor, Goeke, Klein, Onore, & Geist, 2011). In order to fully realize any of these example frameworks, additional professional development (PD) activities must be designed to move teachers or emerging teacher leaders along a dynamic trajectory toward becoming leaders.

Here, we explore a definition of teacher leadership as those teachers who maintain teaching duties and lead from the classroom (e.g. sharing best practices, mentoring, participating in professional organizations/efforts, etc.). We describe a leadership PD activity that employs elements of social network theory to discuss the professional systems in which high school science teachers work and strive to lead others. During the activity with high school science teachers, we facilitated discussions of networks using a visual density scale and solicited feedback on how networks manifested in their professional settings. In order to determine the relevance of the activity, we then analyzed the discourse and generally compared the types of networks that teachers discussed to the types of networks that teachers reported in a separate social network survey. Finally, we analyze network discussion and survey data in light of the diverse activities reported for teacher leaders. The development of our activity and subsequent analyses were guided by the following research questions:

1) To what extent can teacher leadership PD activities be organized around network discussions and network images?
2) How do science teachers make sense of professional network structures?
3) To what extent are visual network images realized in actual teacher leader networks?

4) How do self-reported education networks support or refute the diverse activities and demands ascribed to classroom teacher leaders?
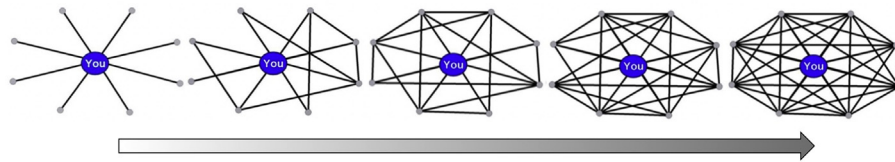
2. Background

Leaders engage in a social enterprise to influence others to achieve (Bass & Bass, 2009). As such, leadership is an emergent property of social systems that arises from individuals working together toward a common goal. Leadership is both a function and outcome of the relationships within the social system (Carter, DeChurch, Braun, & Contractor, 2015; Cullen-Lester & Yammarino, 2016). Professional relationships form larger structures of connectivity, with some structures conferring distinct advantages for leadership (Balkundi & Kilduff, 2006; Burt, Kilduff, & Tasselli, 2013). Network awareness, or knowledge of the broader set and structure of relationships, can contribute to an individual's leadership capacity (Cullen-Lester, Woehler, & Willburn, 2016). Knowledge of the broader structure of relationships is essential to influence, mobilize, and lead others to higher levels of achievement (Krackhardt, 1990). This has been applied in the business world with managers seeking to better lead their employees (Day, Fleenor, Atwater, Sturm, & McKee, 2014), and by analogy may apply to teacher leaders seeking to empower those around them.

Network-enhanced leadership development is a recent model for impacting individuals' and/or collective's network relationships to expand leadership capacity (Cullen-Lester, Maupin, & Carter, 2017). In contrast to traditional approaches that focus on developing the knowledge, skills, and abilities of the individual, the social network perspective emphasizes the relational and embedded nature of leadership. Social network analysis (SNA) provides a rich set of theoretical constructs and visualization techniques to think about complex social worlds in concrete, measurable terms. Thus, SNA moves beyond characteristics of the individuals to focus on characteristics of the relationships in which those individuals are embedded. Network-enhanced leadership development, in particular, focuses on developing knowledge, skills, and abilities regarding the formation, strengthening, and capitalization of network relationships, while using SNA as a pedagogical tool (Cullen-Lester et al., 2017). This may be of immense value in equipping leaders across a range of organizational settings, including teacher leaders, as they consider how to improve the social networks that shape their spheres of influence.

Leadership development practitioners, and their targeted audiences, may benefit from using visual network scales (VNS) in their activities. VNS are stylized depictions of social networks that can clearly communicate some of the main ideas of network theory (Mehra et al., 2014). For example, Mehra et al. (2014) placed network images along a scale of increasing density (Fig. 1) as a new methodology to approximate network characteristics. Graphical representations of network data can quickly give researchers and school leaders a systemic overview of the social structure of an individual (Frank, Lo, & Sun, 2014). VNS have also been deemed helpful in allowing respondents to visualize and understand their own networks (Cullen-Lester et al., 2017). A key component of VNS is the built-in ability to compare and contrast the multiple network images. A teacher in a network can range from being isolated to completely centralized in the network (Baker-Doyle & Yoon, 2011), so reflective practices that examine different scenarios along a scale may be relevant to teacher growth. Using VNS as a basis of group discourse is also likely to reveal the types of teachers who represent different images along a given scale, which may facilitate richer discussion on how or when a certain network is beneficial.

Despite the importance of leadership issues in education, there

Fig. 1. Visual network scale (VNS) depicting ego network images with increasing network density (left to right), described as increasing connectivity between all possible individuals in the network. Based on the work of Mehra et al. (2014).

is not a consensus on how to develop teacher leaders. Management and network theory literature suggest that using network thinking or organizational behavior training can improve leadership capacity (Cullen-Lester et al., 2017; Day et al., 2014). Thus, we have identified VNS as a possible means to provide that training, given the technique's capacity to summarize, illustrate, and compare the professional networks of teacher leaders. In particular, we focused on a VNS depicting network density, because this metric is commonly associated with multiple forms of social capital, defined as the resources, capabilities, and/or goodwill established through an individual's social ties (Burt, 2000; Coleman, 1988).

3. Framework

Our professional development activity and subsequent analyses were conceived through the lens of network theory, in order to more objectively examine educational systems and teacher groups (Penuel, Sussex, Korbak, & Hoadley, 2006). Networks model social systems through a set of nodes and connecting ties (Borgatti & Ofem, 2010). Typically, the nodes represent the social actors (e.g., individual teachers, teams, or schools) and the ties are the various relationships between them (e.g., social support between individuals, collaboration, or resource sharing). A key tenet of social network theory is that the aggregate pattern of ties in a social structure has implications for the actors within it, as well as for the structure itself (Kilduff & Brass, 2010). Ties serve as *pipes* through which resources, information, and influence flow, or *bonds* that facilitate joint and/or multilateral action (Borgatti & Ofem, 2010; Borgatti & Halgin, 2011). They also serve as *prisms* that confer legitimacy or status benefits to well-connected actors (Podolny, 2001). Thus, different positions within a network can confer benefits, opportunities, and/or constraints for actors occupying those positions. This relational view posits that actors controlling information or understanding the nature of networks could derive more benefits than constraints. Directly related to our study, sharing knowledge about network theory, co-constructing an understanding of teacher networks, and examining personal teaching networks in light of their functions, are all designed to foster a relational view in teacher actors and the potential to derive more benefits.

The nature of networks, and their benefits, can be understood through different network characteristics and research typologies related to nodes, ties, and overall structures (Borgatti & Ofem, 2010). Network benefits could be considered related to the ages of contacts (i.e. node characteristics), the types of advice or friendship interactions (i.e. tie characteristics), or positions within the varying shapes and complexities of groups (i.e. structural characteristics). Network theorists have attended to these different characteristics of networks, with structural characteristics often representing a decontextualized or minimalistic starting point for understanding outcomes (Borgatti, Mehra, Brass, & Labianca, 2009). For instance, a Job Embeddedness Model suggests that a greater degree of links or structural embeddedness in the occupational network could impact job turnover by creating "a net or a

web in which an individual can become stuck" (pg.1104) (Mitchell, Holtom, Lee, Sablynski, & Erez, 2001). This structural starting model can explain some variation in outcomes without node or tie characteristics, but has been refined over time. In a later model, Soltis, Agneessens, Sasovova, and Labianca (2013) found that the direction of interactions (i.e. tie characteristics) and whether a contact was obligated to interact (i.e. node characteristics) could explain additional variation in job turnover intentions.

Our activity is grounded in a similar network perspective that structural characteristics can serve as a foundation to explain networks, and future understanding of nodes and ties might be expanded later by asking, respectively, "Who is in the network?" and "What types of interactions are important?" Basic structural characteristics can also be easily depicted in VNS form (Fig. 1) and presented to individuals new to SNA. We chose to visualize structural characteristics associated with social capital outcomes in network literature. Social capital is described as less tangible than physical capital (e.g. equipment, tools) or human capital (e.g. employees, knowledge) and "exists in the relations among persons" that can "facilitate productive activity" (pg. 100—101) (Coleman, 1988). Networks that are structurally open, or less dense, present an individual with different social capital, and associated benefits or constraints, than networks that are structurally closed, or more dense. Open networks allow a central individual to control the flow of information in a network with less connectivity, and have been associated with access to novel information (Burt, 2000) and synthesis of new ideas (Burt, 2004). At the other end of the density VNS, closed networks increase interactions and have been associated with feelings of inclusion (Brown, 1990), collaborative activities, and a culture of norms (Coleman, 1988). The contrast in network structure images and outcomes provides a rich context for facilitating discussions in the activity.

4. Study

Based on our interest in the use of VNS and SNA as teacher leadership PD activities, we designed a network-based leadership activity for a group of 16 Master Teaching Fellows (MTFs) enrolled in a National Science Foundation grant to develop science teacher leaders. As part of the grant, MTFs were completing the third and final course in a Teacher Leader Endorsement Certification program recognized by their state located in the southeastern US. MTFs also engaged in a leadership framework that we have previously described in greater detail (Criswell & Rushton, 2013; Criswell et al., 2018). Briefly, teachers were developed using a framework that combined Dempsey's (1992) four metaphors for teachers as leaders (i.e. teacher as a … fully functioning person, reflective practitioner, scholar, and learning partner) with Goodwin's (1994) notion of professional vision (i.e. coding, highlighting, and articulating the competencies within a profession). As such, MTFs routinely engaged in discourse with each other, 16 novice Teaching Fellows, and project staff related to professional vision, professional identity, leadership plans, and science education [see (Polizzi et al., 2019) for additional program details]. MTFs comprised high

school main teaching assignments in Chemistry (50%) or Physics (50%), and 9 of 16 of MTFs identified as female (56%).

Our professional development activity began with the administration of an online network survey to all 16 MTFs [see (Polizzi et al., 2019) for instrument]. The network survey served two purposes, both as a foundation for the face-to-face activity and as a data source unbiased by the activity. We designed the teacher (i.e. ego) centered SNA survey to capture "Who would you [the teacher of interest] go to for information on teaching content and/or pedagogy?" We specifically asked about information networks (i.e. "information on teaching" as opposed to "teacher friends" or "general advice"), because Coburn, Mata, and Choi (2013) previously found that teacher networks comprised of exchanges of expertise have been shown to persist despite changes at the school-level. Next, for each contact the survey asked, "Of the contacts you listed, who does contact A [B, C …] interact with for information on teaching content and/or pedagogy?" Together, these questions created the foundation of a teacher's network map by identifying contacts (i.e. alters) who were connected to the teacher of interest, and then establishing how connected a teacher's primary contacts were to each other (i.e. secondary ties between alters). We also captured demographic information on the teacher of interest and how geographically distant they were from each contact (i.e. in same school/district/state/nation or international). We piloted the survey with 6 science teacher-researchers spanning secondary education (pre-service and in-service teacher) and higher education (postdoctoral and assistant and associate professor) positions. This allowed us to validate whether the survey question constructs were interpreted similarly across teacher groups, and led to the refined geographic categories and example prompts that were administered to the 16 MTFs.

Approximately two weeks after administering the network survey, we facilitated the face-to-face PD activity using VNS [see (Polizzi et al., 2019) for activity materials]. The activity began by examining the difference between an organizational chart and an actual information network (Fig. 2), in order to illustrate how relationships within an organization matter, and how making our implicit networks explicit can provide advantages when navigating that system. Then we showed two networks with different densities (i.e. degrees of connectedness between contacts) along the density continuum and previewed that networks provide different opportunities and constraints for individuals within them. Next, we unpacked network vocabulary and diagrams by using teachers from popular culture as nodes in a hypothetical network and defined the
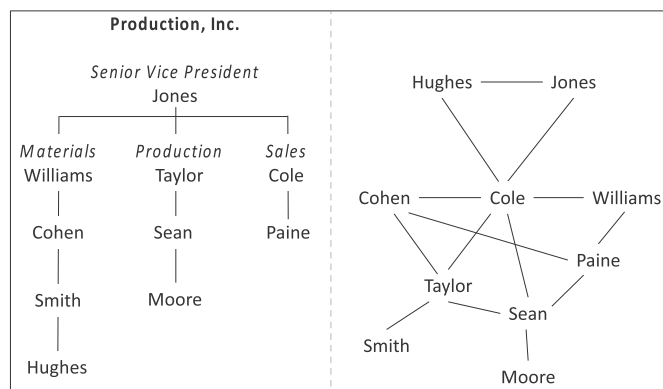
ties as people they "look up to." For example, the "Bill Nye looks up to Captain Kangaroo" network interaction could be represented as an arrow originating from the Bill Nye node and pointing to the Captain Kangaroo node [see (Polizzi et al., 2019) for activity slides]. We then connected the network principles to the teachers' own experiences of the network survey they had taken in the previous two weeks. We walked through the survey prompts and showed how each answer was converted into a part of the network diagram, first with the teacher taking the survey, then primary contacts connected to the teacher, and finally with secondary ties between the contacts (Fig. 3). After that, we shared personalized network maps with the MTFs, and asked them to briefly reflect on how the maps were constructed and the nature of the interactions depicted.

Having built teacher networks along a VNS continuum of increasing density, from only primary contacts (i.e. low density) to many secondary ties between contacts (i.e. high density), we extended the implications of density to social capital. We presented an overview of social capital outcomes, such as access to novel information in low density (i.e. open) networks, and a culture of norms in high density (i.e. closed) networks (Coleman, 1988). MTFs were then encouraged to consider their own network maps, and the social capital represented by the network structures they contained.

In the next phase of the activity, we facilitated discourse through the use of scenarios and conversation prompts. In order to increase the relevance of the activity, we used our knowledge of the MTF professional learning communities within the grant to frame the scenarios. A similar strategy could be used by other facilitators based on the interests of their target teacher groups. For example, in discussion Scenario 1 we showed a network on the more dense, closed end of the continuum, and paraphrased, "Would this network of contacts be helpful if you were trying to gamify (i.e. introduce game elements like levels and badges into) your classroom curriculum for the first time?" In Scenario 2, we showed a network on the less dense, open end of the continuum, and paraphrased, "Would this network of contacts be helpful if you wanted to create curriculum for out of field teachers?" Following those prompts, we broadened the conversation to open ended discussion and paraphrased, "How do networks appear in, or apply to, the education systems in which you operate?"
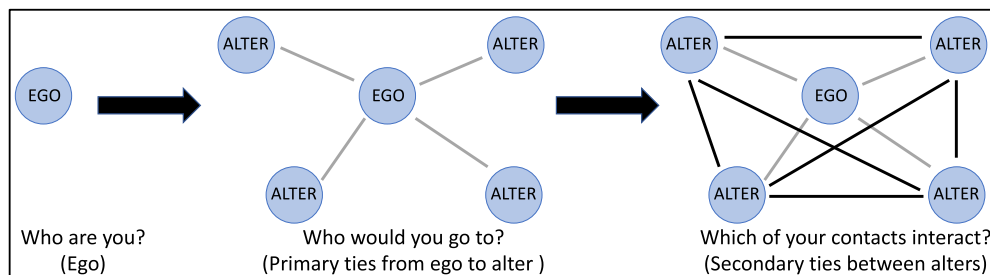
In the final phase of the PD activity, we challenged the MTFs with a view of teacher leadership that seemed contradictory to the open or closed network principles we had previously reviewed: "teacher leaders can increase other teachers' access to expertise and support, thereby creating a more collaborative work environment" (pg 75) (Spillane & Kim, 2012). We highlighted that in network terms, access to novel information or expertise typically speaks to open networks, while a collaborative work environment speaks to closed networks. We directly posed the question, "How can teacher leaders have networks that show mutually exclusive structures?" In response, we asked the group to consider a hybrid network structure that might be found along the middle of the VNS. The hybrid model contained both densely connected collaborative groups for accomplishing tasks (i.e. closed network regions), and a number of sparsely connected sources of novel information or expertise (i.e. open network regions). We concluded with a reflection of how the hybrid model might address Spillane and Kim's (2012) view of teacher leaders, and what could be done if a teacher's personal network map did not contain the expertise or collaborations that might be essential for teacher leadership.

Regarding the time needed for the activities, the online social network survey described above required approximately 30 min for participants to complete on their own schedules. The PD activity took approximately 60 min to complete, including the overview of

Fig. 2. Hypothetical diagrams of an organizational structure chart (left), and the actual network for communicating information within the same organization (right). This contrasting image illustrates that formal titles and intended reporting systems are not the same as the informal network of relationships that communicate information. Based on the work of Cross, Parker, Prusak, and Borgatti (2001).

Fig. 3. Flow diagram of data conversion from social network survey to network diagram. (Left to right) The survey prompts teachers to identify themselves, the contacts they would go to for information related to teaching content and/or pedagogy, and which contacts interact with each other in a similar capacity. This information is extended from a central ego node, to peripheral alter nodes and ties, and finally additional ties between alter nodes.

networks, review of personal network maps, and guided discussions. The PD activity took place during an 8-h monthly meeting and was videotaped.

5. Data analysis

Primary sources of data included network survey responses, and transcripts of group discussions during the PD activity. Electronic survey data were collected from 13 MTFs (81% completion rate) using Qualtrics (Provo, UT) and analyzed using UCINET network software and the Netdraw function for generating network maps (Borgatti, Everett, & Freeman, 2002). Discussions were transcribed for discourse analysis [see (Polizzi et al., 2019) for transcript data] and deductively coded using the characteristics of open and closed networks taken from the PD activity and literature (Table 1). For example, during the PD we listed "access to novel information/ expertise" as a feature of open networks during the unpacking of network structures and social capital, so when an MTF spoke of recruiting new teachers from afar to access new ideas, we later coded the statement as referring to "open" networks. Alternatively, Coleman (1988) described a culture of expectations, obligations and norms found in closed networks, so when an MTF spoke of needing a group to reach a set of common goals or ideas, we coded the statement as referring to "closed" networks. Coding occurred at the participant "comment" level. Comments (e.g. sentence or paragraph) were long enough to determine if a teacher was discussing open or closed networks [see (Polizzi et al., 2019) for method details]. We identified 28 comments for coding from 9 distinct participants in the discussion. Two independent researchers separately coded participant statements as referring to networks that were "open," "closed," or "both," then compared

codes and reached a consensus.

6. Results

6.1. Social networks in teacher professional development

In order to investigate the extent to which teachers could relate to PD organized around network principles and VNS, we coded the teacher group discussion for comments related to open networks, closed networks, or both open and closed networks. Based on our coding of 28 teacher comments, teachers appeared to be able to relate to and discuss network densities along a VNS continuum. We observed distinct discussions related to open (n = 7) and closed (n = 15) networks separately, or together (n = 6). Below, we describe some of the educational contexts in which teachers made sense of each network type and provide exemplar teacher statements.

6.1.1. Teacher discussions of closed networks

The first situational prompt we discussed with the teachers was related to the pedagogical approach of gamifying (i.e. adding game elements like levels and badges to) (Dominguez et al., 2013; Kapp, 2012) curriculum in the context of a closed networks like Fig. 1 (right):

Facilitator: I want to pose this question to the group then. If this [closed network image] is the network that you have, and you want to implement gamification of your curriculum starting from ground zero, do we think this is a good or bad network; or, what features of this network are going to make this successful

Table 1
Characteristics used to code discussions as pertaining to open or closed networks, or both.

Open Network (Low Density) [a]	Closed Network (High Density) [a]
Sparse (Borgatti, Everett, & Johnson, 2013)	Dense (Borgatti et al., 2013)
Structural holes (Burt, 1992)	Closure
Absence of connections	Adding connections
Irreplaceable positions	Structural redundancy
Less visibility	More visibility
Individual transactions	Culture of expectations (Coleman, 1988)
Autonomy	Culture of obligations, norms (Coleman, 1988)
Information outside-to-inside (Burt, 2000)	Sharing of information (Coleman, 1988)
Expertise (Burt, 2000)	Empowering structure
Brokerage (Burt, 2000)	Collaboration (Coleman, 1988)
Access to novel information (Burt, 2000)	Conformity of ideas (Marsden, 1987)
Synthesis of new ideas (Burt, 2004)	Implementation of ideas (Obstfeld, 2005)
Knowledge creation (Fleming & Waguespack, 2007)	Knowledge diffusion (Fleming & Waguespack, 2007)
High locus of control (Kalish & Robins, 2006)	Feelings of well-being (Bearman & Moody, 2004)
Increased influence/power (Brass, 1984)	Sense of inclusion (Brown, 1990)

[a] Comments coded as "both" contained a feature from each category and were often comparative.

or not, if you know nothing about gamification and you just decide, I want to start incorporating this into my classroom?

Teachers provided comments mainly related to closed network structures and their associated outcomes following this prompt. Tess commented on the collaborative benefits of a dense network, "If everybody else is into doing the same thing, it might be effective to work together, you know, each of you can research different parts and bring it together into a program." Aimee further highlighted the importance of a shared vision or common goal for effective collaborative networks:

Then it seems like you might have to get agreement, get everybody to agree that it's a good idea before you can move forward. Maybe—I'm just thinking about this from a standpoint of working together in teams toward a common goal and unless everyone is sharing, or if everyone doesn't think this is a good idea, but everybody needs to be doing the same thing …

Teachers also explored the constraints of closed networks. Aimee touched on the culture of norms that must be considered in dense networks, "There's already an established way of doing things …" Dennis then expanded on the power of teacher culture in connected groups:

You have to figure out a way to share it to hopefully get everybody excited about it. Because with a group that's interconnected like that, they're already talking to each other about it, so if you don't communicate it to that group in a way that gets them all excited about it, you know, it's not going to happen.

In these statements, the MTFs consider dense, closed networks as a force to either leverage or overcome when initiating change in education. By taking a step back from the specifics of the curriculum scenario, they gain an organizational perspective of the challenges. Armed with this network information, the emerging teacher leaders can be more purposeful about the way they recruit individuals to their causes, and how they motivate existing groups.

6.1.2. Teacher discussions of open networks

The second situational prompt we discussed with the teachers was related to the leadership activity of developing curriculum in open networks like Fig. 1 (left):

Facilitator: So we've got another PLC [professional learning community] that I've heard talked about. It's that we are going to … meetings every year, and there's always a biology teacher who is coming into the physics classroom for the first time. Let's try to create some curriculum that is going to target them, and then we're going to try and implement that overall. So my question is, for this [open network image] type of network … what are the good or bad aspects of this network for trying to establish that goal or get to that resolution?

Teachers provided comments mainly related to open network structures and distributed social capital following this prompt. Elaine commented on the access to novel information associated with open networks, "… but also it adds to, it would add to conversation, that new perspective." Dennis also commented on the non-redundant nature of open networks, but focused on the additional effort required to spread information:

Now you have to individually convince every single one of those people that's the way to go. Because they're not going to

reinforce each other at all if they're not talking to each other. So you now have to have four individual transactions to convince them of this.

Unabashedly, the teachers then extended non-redundancy to include the increased power of individuals who were irreplaceable. Dennis looked to the centralized flow of information in the open network:

Or if everybody on the outside believes that person in the middle is a goober, and [the middle] do whatever they tell them to, then I guess that could be effective. Hopefully that person in the middle knows what they're talking about.

Along similar lines, Tess stated, "Well, if you think that person in the middle is a moron, you've got a big problem." Faced with the constraints of open networks voiced above, Lee reasoned through a comparison of both network types in the context of curriculum development:

If I'm in charge of creating curriculum, then I want a network that looks like that [open network image], where I can pull from lots of resources that are going to have different information. I wouldn't want a closed network where, if one person doesn't know it, no one knows it. But if I was trying to get something done as a group, I'd probably prefer the closed group, where we're all pretty closely tied to each other and work well together.

Through his comparison, Lee highlighted aspects of social capital available via densities along the VNS continuum, while simultaneously underscoring the diverse activities that engage teacher leaders.

6.1.3. Educational networks experienced by teachers

After initial discussions of specific network structures along the density VNS continuum, the teachers reflected on their own teaching experiences and shared additional contexts in which networks impacted them. Although the teachers had their personal networks in hand for the discussions, it became clear from statements below that they were extending their understanding of network structures to include the broader network of the school and other leadership activities beyond the professional contact depicted in their personal network maps.

6.1.3.1. Recruiting and staffing.
When considering access to novel information associated with open networks, Melanie shared her school's preference for recruiting at large, rather than from neighboring schools:

We do that a lot at our school, too. People are always surprised that we have so many brand new teachers, but we like the new fresh ideas that they bring, and if they have a lot of recent experiences in education, and so on.

Using an open recruiting network, Melanie's school could be infused with novel ideas that might yield more creative solutions for today's educational challenges. Armed with this network perspective, Melanie appeared to gain a better understanding of the mechanisms at work in staffing, and might advocate for new hires or local transfers based on her department's needs.

6.1.3.2. Interdisciplinary groups.
Open network images invoked a different response from Tess, who had been trying to work

collaboratively with a state broadcasting company to develop science instructional television shows:

> Doing something similar with the [state Public Broadcasting] stuff, like it's been amazing how much you have to negotiate with other people about, 'Oh, this is important to chemistry, for example, because of this, and we should do this in this order.' So I just think having one person then trying to convince, okay, so the person down in the corner [of the open network] thinks that we should do it this way, so now I'm going to talk to you other three about it. But you have a different opinion, so now I need to go back and talk up here, and then I've got to go back and talk to everybody again to try to negotiate a common set of—yeah, vocabulary, or the words that we use, and that these are the most important points of the physics curriculum that I would feel teachers need. So I think that this [open network] would be difficult. It might be a good way to, once you have the agreement, to then divide duties.

We learned from Tess that during the conception of the television show, experts with different backgrounds in science, teaching, acting and television were recruited, but a common goal and normative culture was not firmly established by the unconnected areas of the project. Instead, much time was spent establishing group expectations, after which Tess pointed out the value of dividing the workload. In instances where diverse individuals are assembled for a common purpose, having an effective central figure to broker relationships can ameliorate some of the discomfort Tess experienced. Through additional conversations, it was apparent there were frustrations with the process, although the brokering group did produce an outcome Tess endorsed as worthy of sharing with the education community. Armed with this network perspective, Tess appeared to have a better appreciation of how to efficiently lead an interdisciplinary group toward a common goal in the future, or future seasons of the television show.

6.1.3.3. Nominating teacher leaders.
Discussions also turned to visibility within different network structures. Elaine voiced concern that administrators in need of capable teacher leaders did not always have access to all parts of the school network:

> I think that sometimes you have really amazing teachers who may not be noticed so much. So it may be the administration needs to ask department chairs for nominations, and then, you know, ask that teacher do they want to do more stuff. I mean, recently, I've been nominated to do stuff, and they are things that I didn't necessarily set out to do. I was like, "Okay, I'll do that," and then interviewed for it. So I think some of it is when you just appoint teachers and like, "Oh, and I get a stipend!" … they might not be the best choice. So do more of a nomination/application type thing, so they [administration] have to ask them [the strong teachers].

This situation speaks to an open network, in which individuals do not have access to all other individuals, resulting in less visible regions of the network. If value resides in the less connected region of the network, it may be less likely to be called upon. One solution to increase visibility would be to spend time increasing connections, and therefore visibility, in a denser network. Instead, Elaine's proposes to more strategically sample the existing network for individuals, or brokers, who have access to otherwise inaccessible regions of the school network. By a distributed nomination process, Elaine argues more "amazing teachers" and fewer "I get a stipend!" teachers might obtain leadership opportunities.

6.1.3.4. School initiatives.
The topic of leadership opportunities prompted additional conversations around the educational context of teachers spearheading initiatives. Tess considered the need for dense collaborative networks to fully enact an initiative:

> I think after this conversation, what you made me think of, like if you're only sending two people from each school … you're not interconnecting enough people to other people. And I realize there's a cost function to that … maybe it's not possible to send 10 people from every school, but then you take, you know, 10 people from every school with 10 people from all these other schools, and you have interconnected all those people with all of those people. So then when they come back to the school, there's not just one or two people as a source of information for the whole rest of the school. Then there's a lot of people who have each other—those 10 people or whatever—and now, if I'm not one of them, I have lots of people I can connect to who are then connected to lots of other people as far as sharing ideas and things like that.

Lee then contemplated the temporal nature of initiatives, which need a critical mass to be effective:

> So if you don't have the budget to get some people from every school, you could pick a few schools. It's better to be effective in a few schools than not effective in any schools at all. And that could grow from there.

These comments find benefits in the redundancy of the closed network structure, considering that initiatives may grow over time if key individuals do not turn over during the initiative's timeline.

6.1.3.5. Professional organizations.
Finally, teachers considered the network implications of professional organizations. Aimee highlighted that by connecting to a larger, dense network, she could broker information for her school network:

> I'm the dot in the corner. I'm the purple dot, but I've got this connection to the green dot that nobody else has. The green dot is all that's useful in all the information that we collectively have, then I am connected to Noyce [NSF Teacher Leader Program] and I'm the only one connected to green, and anything I bring back I can share with everybody at my school.

Aimee sees that connecting to existing networks, not just individuals, can benefit her school. Tess moves beyond the Noyce community and generalizes to the Advanced Placement (AP) network:

> What I was thinking about with these questions was that this didn't tie into anything like the larger network. Like, you know, where would I go to get new info or new ideas would probably be to go to a conference, which would tie me into a whole other set of networks. If this is only individuals, not like connected to organizations, where you could get a whole lot of—Like what we were talking about with the AP stuff earlier, the AP online resources came up. That's a place to get some support as well as the new ideas. So that's something else to consider as part for your overall network, or the other network you can tap into.

Both scenarios provide the teacher with support from a dense network, while allowing them the power to broker information between organizations.

6.2. The density and structure of teacher information networks

During the PD discourse analysis, we observed that MTFs discussed important roles for both open and closed networks in education. Therefore, we were interested in determining the types of network structures that the emerging teacher leaders actually cultivated in their professional environment. We returned to the SNA survey data that had been used to create network maps for the PD activity, but this time we analyzed the network density using UCINET. Network density is a basic quantitative measure of ego network structure, defined as the degree to which all contacts in a network are connected with all other possible contacts. Density can be quantified along a VNS continuum (Fig. 1), with at one extreme, networks capturing all possible connections having a high density of 1, and at the other extreme, networks with only connections between the ego and individual contacts having a low density.

In our study, no teachers reported a network that was completely open or completely closed. Instead, all teachers reported networks that were less than 50% dense (Fig. 4A). On average, network densities corresponded to approximately 29% of all possible connections. As a consequence, each network was missing more than half of all possible connections between a teacher's contacts, and visibly appeared to have open regions (i.e. structural holes) where connections were absent. Inspection of both the most closed and open networks in our sample, corresponding to Henry (Fig. 4B) and Marty (Fig. 4C) respectively, showed contacts that were not maximally connected, consistent with density calculations <50%.

6.3. Hybrid networks

During the PD discussion, we challenged the MTFs with a hybrid network model of teacher leadership containing very dense and very sparse regions within a single network. Our initial analysis of the networks revealed densities <50%, which might be explained by either hybrid-style networks (e.g. some individuals in the network highly connected in groups, while others only connected to the ego), or a low number of evenly distributed ties (e.g. all individuals in the network connected to 1–2 others). In both of the above network images (Fig. 4B and C), we noted that the number of
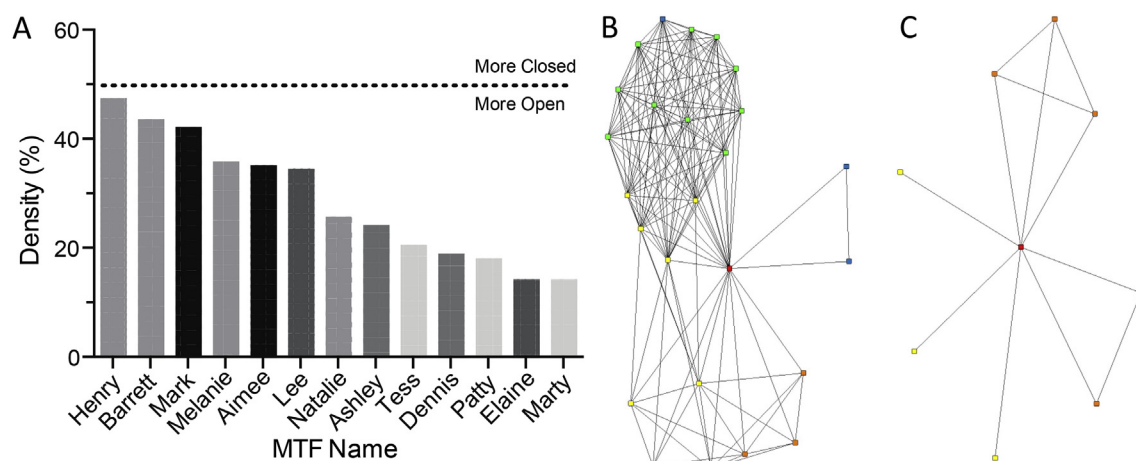
connections was not evenly distributed over all contacts. For example, the average density we observed for Henry (Fig. 4A and B) was not the result of each contact having connections with a low number of randomly distributed ties. Instead, we observed a group of state/district contacts that was densely interconnected (Fig. 4B, top), a distinct group of district/school contacts that was interconnected (Fig. 4B, bottom), and a pair of national contacts that was connected (Fig. 4B, right). Connections between these groups was minimal, or absent in the case of the national pair, and contributed to a hybrid-style network structure with lower overall density.

Contacts who were connected to the ego, but none of the other alters, also contributed to a hybrid-style network structure and lower overall density calculation. For example, the average density we observed for Marty (Fig. 4A,C) was depressed by the presence of three contacts that were isolated from more densely collected groups of contacts. A total of 23 isolated contacts were present in 9 of the 13 teacher networks, and just as in the case of Marty, the isolated contacts were separated from one or more groups of more densely connected contacts, as might be expected for hybrid-style networks [see (Polizzi et al., 2019) for individual network maps]. In order to better understand the types of hybrid network structures that were important for teacher leaders, we also examined the isolated contacts for how geographically distant they were from the surveyed teacher. We found that 43% (or 10/23) of isolated contacts appeared as (inter)national contacts. This finding indicates that the largest proportion of sparse contacts in hybrid networks are at longer geographic distances, and supports a teacher leader model of local dense networks and distant sparse contacts.

7. Discussion

7.1. Teacher leadership activities can be organized around network concepts and images

Network-enhanced leadership development models have been advocated for in the management sector to empower leadership through an understanding of the formation, strengthening, and capitalization of network relationships (Cullen-Lester et al., 2017). Network-based PD has also been investigated with teachers in higher education related to instructional improvement (Van Waes

Fig. 4. Ego network densities. Density in this information-based network was defined as the number of connections present in an ego's network, divided by the number of possible connections in the network. (A) Distribution of teacher densities. Pseudonyms are listed across the x-axis for each of the surveyed teachers (n = 13). Average density with standard deviation is 28.9 ± 11.6%. The 50% cutoff is depicted by a dashed line to illustrate that all teachers reported networks with more open than closed structures. (B) Diagram of most dense teacher network in sample corresponding to Henry. (C) Diagram of least dense teacher network in sample corresponding to Marty. Nodes are colored by closest geography relative to the ego (red) to show contacts in the same school (orange), district (yellow), state (green), or nation (blue), noting that a teacher at the same school is listed only at the school level, despite being in the same district, state and nation.

et al., 2016, 2018). Here, we adapted this leadership strategy from the human resources and management fields, and applied it to teacher leadership. We proposed that using VNS as a PD tool can allow participants to explore network theory and organizational behavior, both of which are advocated for in the network-enhanced leadership development model. VNS provides several network images that target a single concept from network theory and generates a frame of reference for internal comparing and contrasting. While comparing visual models may seem intuitive to teacher educators as a pedagogical technique for guiding reflection and facilitating discourse, to our knowledge, VNS has not been reported as a focused PD activity. In this activity, we found that teachers successfully engaged in group discussions of hypothetical or real-world scenarios using network principles despite limited exposure to SNA and VNS. In the 1-h activity, the participants generated 28 distinct discussion points related to networks that were later coded. This generative conversation was likely influenced by the fact that teachers find themselves embedded in numerous implicit networks related to teacher leadership, which can be made explicit with purposeful facilitation.

7.2. Networks move science teacher discussions toward broader leadership issues

York-Barr and Duke (2004) described what teacher leaders "do", such as improve school systems through mentoring and empowering other teachers, but did not define the processes through which teachers begin to think as leaders in more systemic terms. Larrivee (2008) has argued that "carefully constructed guidance" (pg. 345) is needed in the process of promoting critical reflection on the teaching profession, such as challenging the status quo of power and control, and considering practices within broader sociological, cultural, historical, and political contexts—things we might expect leaders to do. We provide our network-enhanced leadership activity as one mechanism for providing that guidance and moving teacher discussions toward leadership topics. By helping teachers think about the systems in which they are embedded, the resources that are available, and the goals they want to achieve, there is a natural shift to systemic thinking, questioning how to redistribute power and control, and broader contexts.

In support of this idea, we highlight the two discussion scenarios dealing with curriculum development. At first glance, curriculum development might be seen as an individual teacher's project, primarily concerned with where to find information to take back to their classroom. However, given the preceding discussion of network concepts, the discussions turned to who in the system had information, and were they in a position that was ready for collaboration, or did something in the system need to change to make it more collaborative. Further, the open ended discussions did not generally focus on a single teacher's actions inside their own classroom, but moved to more outward facing, systemic issues, consistent with Wenner and Campbell's (2017) description of teacher leaders enumerated in the introduction. Leadership related topics included recruiting and staffing, interdisciplinary groups, recognizing other teachers' abilities, professional organizations, and school initiatives. Similarities and differences voiced in the group discussion allowed teachers to make sense of different professional networks, and how they might be mobilized both for personal benefits and leadership opportunities.

7.3. Science teachers find meaning in both open and closed network structures

During the teacher leadership activity, we observed that MTFs were able to discuss open or closed networks. In the cases of open networks, value was often placed on access to novel information and expertise, rather than other outcomes associated with open networks in the business world, such as autonomy or the power to broker individual transactions (Table 1, left column). The MTFs appeared to have found meaning in the networks related to empowering the systems in which they were embedded, instead of focusing on personal gain. Turning to the cases of closed networks, value was often placed on collaboration and consensus building, rather than other outcomes associated with closed networks from the social sciences, such as feelings of well-being and belonging (Table 1, right column). It is possible that the higher experience levels of the MTFs caused the latter emotional features to be de-emphasized, suggesting that feelings of inclusion afforded by closed networks might be more important for novice teachers who were not included in our sample. It is also not immediately clear why twice as many comments were related to closed networks compared to open networks. One possibility is that the leadership focus of the group tended to identify with discussions of collaboration and communication more than accessing novel information. Another possibility derived from the network maps [Fig. 4 and Polizzi et al.(2019)] is that a higher proportion of contacts were involved in dense communication networks compared to being isolated, which translated to MTFs thinking proportionately more about their dense networks. Yet another possibility is related to the egalitarian norms found in many schools. MTFs may have risen as teacher leaders in part due to personal tendencies toward equal access and sharing networks, or responded based on experiences with dense interactions in department- or grade-wide initiatives. In any case, the discussed values of both open and closed networks were confirmed in the network maps generated before the PD discussion. MTFs reported via survey that their actual networks were somewhere on the VNS continuum between fully open and fully closed networks, and then they verbally indicated how both open and closed networks were important in their education settings.

7.4. Teacher leaders benefit from a hybrid network with distinct open and closed structures

Spillane and Kim (2012) have advocated that "teacher leaders can increase other teachers' access to expertise and support, thereby creating a more collaborative work environment" (pg 75). In network terms, access to expertise and collaboration have been associated with open or closed networks, respectively (Table 1), and might be viewed as mutually exclusive options for an overall network structure. Reagans, Zuckerman, and McEvily (2004) explored an alternative network structure that includes distinct open and closed areas within business networks. In their hybrid network, the combination of dense local ties and more sparse ranging ties were proposed to increase an individual's social capital and a work team's performance. The local-distant nature of ties in the hybrid model seems consistent with Tess's comments about leading through accessing novel information from a conference resource and then bringing it back to a dense network of school colleagues lacking similar access to the information. Our analysis of the network maps provides additional evidence for this model, as densely connected work groups visually included school, district and state contacts, while the largest proportion of isolated contacts occurred outside the state in which a teacher worked. Given the national scope of education and teacher professional organizations, it is possible that teacher leaders may need to adopt a hybrid network structure in order to gain social capital that can enhance individual and collective performance.

This hybrid model may also help account for the diversity of activities and responsibilities ascribed to teacher leaders in reviews

of what teacher leaders do and why informal teacher leadership may be conflated with formal leadership of teachers (Wenner & Campbell, 2017; York-Barr & Duke, 2004). Teacher leader responsibilities in mentoring junior teachers and participating in school change and improvement are consistent with our observation of higher numbers of contacts and higher density groups at the more local, school and district levels. Additional activities that may be characteristic of teacher leaders, such as participating in professional organizations, or building partnerships with colleges and universities to prepare future teachers (York-Barr & Duke, 2004), are not necessarily tied into the local dense network. Instead, the teacher leaders may represent their schools as more singular representatives or brokers, and make less dense connections through their state or (inter)national spheres of influence. Given the demands of classroom teaching alone, it may be untenable for teacher leaders to have overly dense networks, in which national and school level contacts are collaborating, or multiple dense collaborative groups in different spheres of influence. However, it is also tempting to consider the dynamics of a hybrid structure in terms of formal and informal leadership positions. At a point in which high density at the local school level begins to be exchanged for higher density at a district, state or national level, is a teacher more likely to transition into more formal roles as a principal, curriculum coordinator, or policy advocate?

8. Limitations

This study may have limitations in generalization, given the small sample size and other leadership activities the MTFs engaged in over the 5 years of support. For example, MTFs were grouped in cohorts spanning school districts, supported in leadership activities at local and state levels, and exposed to national teaching experts through grant funding. In addition, our study only examines one particular type of network characteristic even though there are many other network features that might be important for teacher leaders (e.g. tie strength, ego network heterogeneity, role model homophily, etc.). We also did not investigate the accuracy of self-reported network interactions disclosed during the activity discourse, or during the network survey, suggesting the teacher networks should be treated as perceived networks. However, our intent with this study is to demonstrate the utility of VNS to discuss network theory to promote network-enhanced professional development in teacher leaders. Although we focused only on network density, our preliminary use of VNS seems appropriate for other PD with STEM educators, who often teach through the use of visuals and system diagrams (e.g. food webs). For those in STEM teacher (leader) preparation and education research, we see a number of potential applications for VNS studies. We hope our study encourages additional examination of VNS in both the research and practice of developing teacher leaders.

9. Implications for VNS

VNS has been proposed as a methodology for a more direct examination of SNA constructs such as density and betweenness, rather than calculating these values from surveys of secondary ties (Mehra et al., 2014). Subsequent SNA studies have incorporated VNS as a methodology and time saving tool, but it is unclear the extent to which the two distinct methods (i.e. VNS vs secondary ties) routinely provide similar descriptions of the same network characteristic. In our study, we analyzed the easily conceptualized network characteristic of density, and gathered data from VNS and secondary tie methods. Although our VNS and secondary tie data were qualitative or quantitative, respectively, and our VNS data was collected from a group activity, our measures do provide a degree of

general agreement between the methods. Teachers discussed the professional relevance of both open and closed networks on the VNS continuum, and they provided secondary tie data that was neither completely open nor completely closed, but instead had regions of open ties and regions of closed groups. This finding of general agreement between density constructs from VNS or secondary ties appears to be consistent with the findings of Brands, Menges, and Kilduff (2015). In their study, two quantitative network data sets were collected using either traditional secondary ties or the new VNS measures. Correlations found between centrality, cohesion, gender, and charisma in the traditional secondary ties data set were also found in the VNS data set, indicating agreement in the methodologies (Brands et al., 2015). Based on the utility of VNS, we propose several possible uses for VNS in leadership studies in the future, as detailed below.

9.1. Measuring teacher sphere of influence

In our study, Tess described a leadership opportunity derived from leveraging her contacts in the broader community to bring back novel information/expertise to her school working group. Our examination of the network maps showed multiple examples of contacts inside and outside the teacher leaders' schools. We propose that examining a VNS of the geographic range of teacher networks at the school/district/state/(inter)national levels may serve as a way of quickly analyzing spheres of influence and teacher leadership capacity.

9.2. Longitudinal measure of how teacher leadership develops

The teachers in our study spanned experience ranges of approximately 6–20 years in the classroom. We observed a range of network sizes and densities, and are interested in possible relationships between experience and network characteristics, or how teacher leader networks change over time. We propose that a VNS of size or density could be used at multiple time points, or in a reflective activity in which teacher leaders select the network characteristics that represent their development over time. For example, teacher leaders may select network images that indicate in year one of teaching they had large, dense networks that were trimmed over time to form a hybrid-styled network image, and indicate they were externally validated for their teacher leadership at that time.

9.3. Professional development activity in teacher leadership programs

Finally, our data have implications for the way that teacher leaders are prepared. SNA has been incorporated into managerial training schemes and MBA curricula, where it can help individuals take an organizational perspective on workplace issues, rather than an idiosyncratic perspective that their issues are unique and insurmountable. To this end, effective managers are expected to understand the system in which they operate and how to navigate the challenges to satisfactory conclusions. We see the potential for teachers to receive similar systems training using VNS to equip them with social network theory. In doing so, teacher leaders can become similarly empowered to navigate their professional systems in higher functioning ways.

9.4. Selective criterion for teacher leadership opportunities

Selecting participants for an extended teacher leader program, or even the single teacher leader activity we presented here, requires defining a set of criteria for inclusion and screening

candidates. Based on the data collected in this study, VNS may serve as a means to assess the leadership potential of teachers, since GPA or year of experience may not depict the relationships that must be leveraged by leaders. For example, our activity with teacher leaders revealed networks of a general size with both open and closed regions. It may not be advisable to select teacher leader candidates who select images representing a diminutive network size, complete isolation in their practice, or only a dense network of redundant contacts at the school level. Additional leadership studies are needed to determine those desired criteria.

9.5. Diagnostic for teacher leadership outcomes of an intervention

Teacher leadership initiatives and activities take many forms but are likely to include capitalizing on interactions and increasing spheres of influence. Based on the diversity of network densities and contexts that were captured in our activity, we propose that VNS covering a range of network properties, such as density and reach could be used to rapidly assess the ways in which an intervention changed participants' interactions. For example, VNS data from before and after our five-year teacher leader project may have shown that initially MTFs were not connected to stakeholders beyond their district, but after the project, they were connected at state and national levels as a positive outcome.

Acknowledgments

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