Person-centered and qualitative approaches to network analysis in physics education research

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Network analysis has become a well-recognized methodology in physics education research (PER), with study topics including student performance and persistence, faculty change, and the structure of conceptual networks. The social network analysis side of this work has focused on quantitative analysis of whole-network cases, such as the structure of networks in single classrooms. Egocentric or personal network approaches are largely unexplored, and qualitative methods are underdeveloped. In this paper, we outline theoretical and practical differences between two major network paradigms—whole-network and egocentric—and introduce theoretical frameworks and methodological considerations for egocentric studies. We also describe qualitative and mixed-methods approaches that are currently missing from the PER literature. We identify areas where these additional network methods may be of particular interest to physics education researchers and end by discussing example cases and implications for new PER studies.

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I. INTRODUCTION

Network analysis has become recognized in physics education research (PER) as a lens for studying complex systems in terms of both the entities and the relationships between them [1–3]. One broad division in this work is whether or not the network is social—whether the nodes represent people or other things like ideas. In the first case, a network framing offers tools for considering many-body situations such as classrooms, where individual outcomes are expected to arise in collaboration with others [3,4]. In the second case, networks may be used to study the structure and configurations between concepts, such as items in conceptual inventories [5] or the knowledge of physics teachers [6]. This paper focuses on the first case or studies using social network analysis (SNA).

Another way to classify analyses is by whether the study concerns whole or personal networks. In whole-network approaches, a population boundary is defined (e.g., all students in a class section or all items on a concept inventory) and researchers seek a complete accounting of ties between this set of nodes. Egocentric or personal network analysis is a complementary framing that studies single actors and their surrounding connections. To date, almost all PER network studies have used whole-network approaches, and the primary aim of this paper is to bring egocentric approaches into the methodological domain of PER. Because many of these studies use qualitative methods, we also give significant attention to qualitative and mixed-methods network methodology.

In egocentric social network studies, the focus is on an individual actor—the ego—and mapping all of their connected people—alters—for one or more types of relationship. In many cases, the research also considers ties among alters, and this information comes from the ego rather than from the alters themselves. Multiple ego networks are typically collected and may be analyzed qualitatively [7,8], quantitatively [9,10], or with mixed methods [11,12]. Networks may overlap if the egos have alters in common, but this is not required, and in many cases, the egos do not know each other at all. Unlike in whole-network studies, the goal is not to comprehensively sample one bounded space but to learn about the size, structure, content, or functions of the personal networks of some type of person.

This approach offers new applications of networks in PER, but it uses different theoretical framings and sometimes different methods compared to whole-network studies. In this paper, Sec. I begins by briefly reviewing recent network analysis trends in PER, noting the methodological space not mapped by that work, and framing the rest of the paper in terms of several "big questions." In Sec. II, we lay

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out key dimensions in the design of ego network studies. Section III introduces common theoretical frameworks used to guide study design and Sec. IV reviews key methodological results with a focus on those bearing on egocentric, qualitative, or mixed-methods work. Section V discusses several example cases from the education research literature. Section VI concludes by discussing possibilities and implications for network studies in PER. One of the strengths and challenges of network analysis is that it spreads over many disciplinary and network-specific journals, so throughout the paper, we have tried to include a diversity of resources that may not be familiar to Physical Review Physics Education Research readers.

A. Network analysis in PER: Recent trends

Network analysis concerns the study of *nodes*—people or other entities (e.g., a department or organization)—connected by *ties* (also called links, connections, or edges). Network analysis has roots in both sociology and mathematics and lends itself to a rich diversity of research questions and contexts. In education, it has often been taken up because of its potential to describe complex systems of people and relationships at many scales [13,14]. However, reviews of networks in education have noted a dominance of quantitative descriptive studies which explore a relatively limited range of learning contexts or research questions [13,15,16]. In PER, the most common set of methods and study contexts shares this bias and this potential for expansion.

An all-inclusive review of network analysis in physics education, based on preliminary searches, would span hundreds of papers and thus constitute its own project. Commentaries by Bruun [2], Brewe [1], and Traxler [3] give overviews of broad trends while this larger task is outstanding. For this paper, we examined the recent use of SNA in PER, focusing on methodological and topical trends as the use of networks expands in the field. We performed keyword searches [17] covering April 2017–November 2023 on ERIC, the Web of Science, Google Scholar, the proceedings from the Physics Education Research Conference (PERC), and the International Research Group on Physics Teaching (GIREP). We classified the relevant results by whether they used a whole or ego network approach and whether they used qualitative, quantitative, or mixed methods. Other possible categories (e.g., study population) were not distinguished because our primary interest lay in probing the methodological space.

Of the 21 papers we found, 18 used quantitative methods, 2 used mixed methods, and 1 used qualitative methods. (Two papers that coded video data to generate networks [18,19] are grouped as quantitative rather than mixed-methods because the purpose of the coding was to count the presence or absence of network ties, not to otherwise describe details of the interaction.) All but one study used a whole-network approach. To our knowledge, only two egocentric-focused PER network papers have been published: one by Goertzen *et al.* [20], before the period of this sample, and one by Wu *et al.* [19]. The themes explored by the papers include function and structure of social networks [18,19,21–29], persistence in physics [25,30–32], academic performance [25,32–34], changes and development of social networks over time [18,28,32,35], assessing the effectiveness of specific programs [18,29,34,36], and theory [1,3,37]. One area that is largely absent from PER, but rapidly growing in other educational domains, is the combination of network analysis and learning analytics to study online or in-person learning environments [15,16].

Although the incorporation of SNA in PER is relatively recent [1], the method contributes to physics education by providing relevant tools and a theoretical perspective on how connections between students and their peers or instructors affect different aspects of education. SNA also has a wealth of methods that have not yet been applied to PER. In particular, qualitative and egocentric approaches are virtually unexplored despite their unique potential contributions to the field.

B. Framing egocentric vs whole-network approaches

Complete networks, or whole networks, are derived from a sociocentric (as opposed to egocentric) approach to network analysis [38,39]. This approach is helpful in assessing the position of all nodes simultaneously within a network and is used when the research aims to understand how a specific group is structured. It rests on the assumption that the researcher has access to the entire group and knows its boundaries [39]. A physics class [27] or a university department [40] are examples of complete networks in PER.

The egocentric approach focuses instead on one specific node, the *ego* (the person interviewed, surveyed, etc.) and all their connected nodes or *alters*, enabling comparisons between the networks of different egos [38,39]. Ego networks can be extracted from whole networks [38,41], but it is common to collect data from egos directly. This can be helpful when it is not possible to access the entire population of interest. Ego networks can also be a useful approach for networks that do not overlap, but where researchers still want to better understand the connections of members of different groups [39].

Figure 1 shows an example of the difference between these two approaches to social networks. The first panel might represent a classroom network collected in a typical PER study. The second panel shows an alternate focus, where the networks of selected students are highlighted for a focused study (one route for mixed-methods approaches, see [42,43]). More detailed data collection centered on those egos could include many people outside the class roster boundary such as teaching assistants, friends, or family members. Figure 2 shows those egos might have

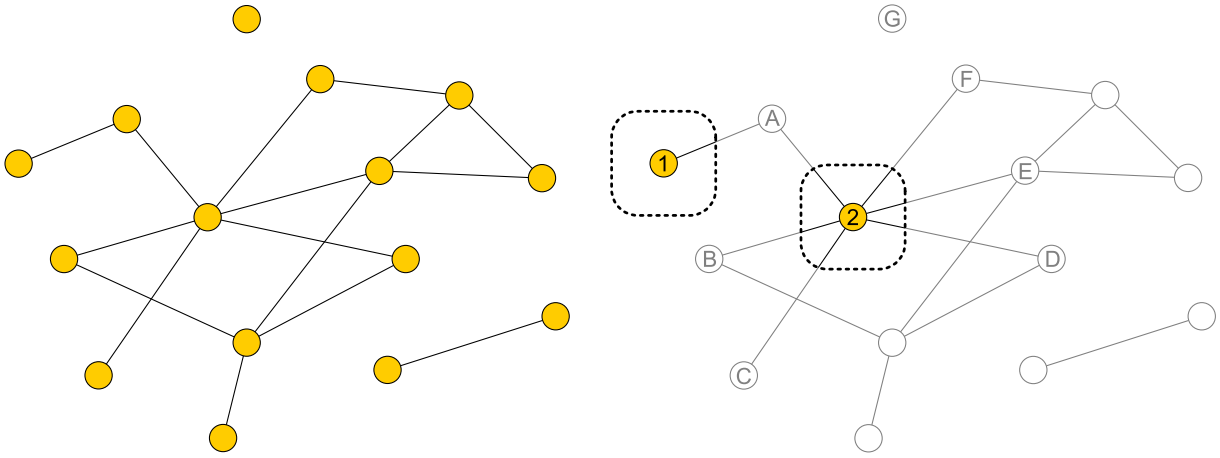

FIG. 1. A sample whole network from a class (left) and possible ego network focus (right). Egos (1 and 2) and several alters in the class (A–G) have been labeled.

important ties not visible in the classroom network but salient from the egocentric point of view. The first panel shows the original classmate ties plus new nonclassmate alters (triangles, who might be classmates in other courses). The second panel adds information: alters are positioned according to closeness and line types indicate different ties (e.g. in-class interaction as a solid line and participation in a study group as a dashed line).

Whole-network studies are often quantitative, reporting on characteristics such as the distribution of links between actors, membership in subgroups or communities, or the flow of resources or information through the network. These same characteristics may also be described qualitatively for smaller networks, for example, to characterize the discussion structure of a class [44]. Alternately, qualitative work may explore beyond these metrics, as discussed by Hollstein [8]: mapping unknown community structures [45], analyzing the interaction practices of a community [46], or querying participants about their assessments or meanings of relational ties [47]. These kinds of ethnographic explorations are best known in fields such as anthropology, but discipline-specific science perspectives are rare and would be a valuable addition.

Egocentric studies are also used for quantitative research questions, for example, about the variation in sizes or densities of personal networks or the differences in tie strength between certain interaction types [9,18,19]. They offer additional range for qualitative or mixed-methods studies that focus on a "depth over breadth" approach. Ego networks are especially suited to investigations where the nuances of network relations are key, such as questions about the content or meaning (beyond binary existence) of ties. For example, a network study of physics majors in a department might ask egos who they do homework with, but also how they perceive the expertise of those people and whether the study group has been stable or changing over time. These details could be a valuable addition to work on identity development, where recognition is a key part of

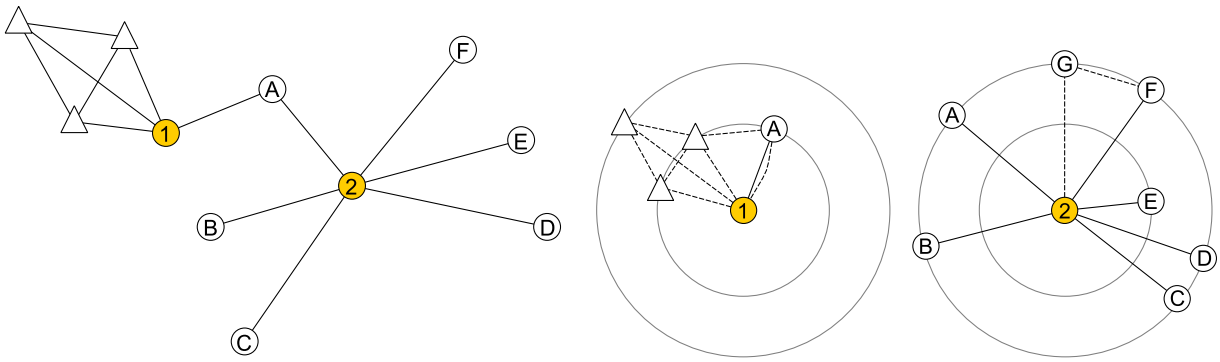

FIG. 2. Personal network connections for the two egos selected in Fig. 1. On the left is the subset of the class network with direct connections to these two egos (alters A–F) plus additional alters from outside class (triangles). On the right, the same alters are arranged by closeness to ego and to each other. Dashed or solid lines denote separate types of ties, and both egos have ties that were not apparent from the original whole-class survey.

theory [48,49] and might be reflected in the topology of peer networks.

In both whole and egocentric network studies, it is axiomatic that the connections between people are fundamental to understand their lived reality. Whole-network studies position themselves to some extent "above" (or at least outside) the group in question, in effect describing the forest instead of individual trees. Ego network studies are situated more in the perspectives of individuals, understanding the shared social reality as a collection of overlapping personal worlds. This person-centered approach can be taken up through different theoretical frameworks and data collection tools, which we discuss next.

We organize the rest of the paper in terms of several "big questions" that might be asked when planning a research project. These questions are potentially useful in all network studies but especially helpful in sketching a map of this newer-to-PER methodological space:

- What interests you about the network? (Sec. II).
- Why do you think the network is important? (Sec. III).
- How do you intend to study the network? (Sec. IV).

Section V discusses several examples from the educational literature in light of this material, and Sec. VI revisits these questions for PER.

II. CONCEPTUALIZING: WHAT INTERESTS YOU ABOUT THE NETWORK?

The first "big question" starts with curiosity: what interests you about the network? Studies can start from an overheard bit of conversation, an observation that some students in a class seem to gravitate toward each other, an experience of a close graduate school cohort or many other threads. One brainstorming tool is to think about different possible dimensions of networks that can be foregrounded. Perry *et al.* [38] (chap. 1) articulate four dimensions:

- *structure*, such as the network's size or patterns of ties;
- *function*, such as the type of exchanges or resources available in the network;
- *strength*, such as the relative durability or variety in bonds;
- and *content*, such as attitudes and beliefs present in the network.

All of these relate to the dual nature of network systems —the fact that they are built of both nodes and links—but focus on different facets of that duality. Many PER network analyses focus on structure or functional questions in the case of more specific prompts such as homework help [26]. However, the number of strong ties in students' departmental networks might be an important indicator for retention or colleagues' views about teaching might be highly relevant for departmental reform efforts. Later decisions in the study design can be clarified by thinking around these dimensions and which one(s) to highlight.

III. THEORETICAL FRAMEWORKS: WHY DO YOU THINK THE NETWORK IS IMPORTANT?

Various theoretical frameworks have been used in social network studies, based on different mechanisms that might be important in the participants' context. In some cases, researchers are primarily interested in the effects of network structure on the actors, while in other cases, the focus is on what causes that structure to exist or change [50]. In terms of "big questions," this point can be framed as "Why do you think the network is important?" Below, we expand on three possible answers to this question which have been well developed in the network literature [38].

A. Social support: Importance to well-being

The social support framework focuses on how network ties connect people to resources that sustain them in times of difficulty. These supports might be instrumental (practical assistance), emotional, appraisal (for example, of a problem), or monitoring [38] (chap. 1). In literature on educational or workplace networks, instrumental and emotional supports are the most commonly discussed. For example, Atherley *et al.* [51], in a mixed-methods study of transitions in medical student clerkships, found that both emotional and instrumental support ties changed greatly over the first 4 months. Peer ties grew especially prevalent due to the importance of venting and sharing professional norms picked up during clerkships. In another example, Skahill [52] studied the social support networks of first-year students at a technical arts college and found that residential students experienced a sharp density drop and need to rebuild their networks compared to commuter students who had more local ties. However, residential students who formed new ties reported significantly greater feelings of success at school, and these new school-centered networks may have boosted their persistence.

Additional overview and examples of the social support literature for network studies are given by Refs. [38,53,54]. This framework might be especially useful for investigating retention and persistence (e.g., of students in a physics major) or difficult transitions (e.g., beginning a teaching career or graduate program). It can also help to clarify the kinds of resources that are important, for example, in distinguishing multiple sources of support such as emotional versus instrumental or material connections.

B. Social capital: Importance to power and brokerage

Social capital, as used in network analysis, refers to access to resources in a social network. Lin [55] identifies three elements: the resources are part of a social structure (embeddedness), accessible to individuals (opportunity), and used in purposive actions (use). There is a conceptual overlap between this framing and the social support literature discussed above. However, social support studies tend to focus on the well-being of network members, while

social capital studies orient toward more external questions of power and brokerage. An influential work in the development of this area was Granovetter's "The strength of weak ties" [56], which discusses how important information such as new job leads may come from more tenuously connected parts of personal networks, as opposed to the denser set of strong ties in a person's core relationships. One explanation for this trend is that peripheral network members are more likely to bring novel and nonredundant information. (As an example of this mechanism, one author (A. T.) recently changed jobs after a lengthy search. The U.S.-based PER community is relatively close, and PER jobs generally appear in a small number of advertisement areas, providing few new suggestions from U.S. contacts. International colleagues forwarded job openings from the broader science education field that never appeared in venues such as APS Physics Jobs, and one of these ultimately resulted in a relocation to Copenhagen.)

This idea—of the different benefits to having both dense and sparsely connected areas of one's network—has been extensively studied in workplace contexts. A key finding of this work is the importance of "structural holes," those parts of a network that do not communicate directly with each other and thus exchange little information [57]. Structural holes give rise to brokers, people whose connections span the hole and thus have the opportunity to share perspectives, communicate best practices, or synthesize new ideas [58].

In educational contexts, social capital has been used to frame students' resources and access at various ages. In one example, Rios-Aguilar and Deil-Amen [59] map and characterize social capital in the networks of Latina/o university students. By distinguishing nine categories of social ties such as family, clubs and organizations, and professional networks, they were able to identify how students moving from high school to university tended to have capital relevant to "getting in" but far fewer ties that could help with strategizing success in college or planning professional trajectories. Their analysis also revealed regions of networks where these ties could be sustained and strengthened, such as bridge programs (in this example, a summer program where incoming college students received extra academic and networking preparation).

Knaub *et al.* [60] suggest an alternate focus of social capital that can benefit education researchers, by focusing on the ties in academic departments as sites of instructional change. They frame the central question of the social capital perspective as "what is being exchanged in a tie?" and note the importance of weak ties, access to new ideas, and brokerage in studying these social systems. In our own study of the professional support networks of women and LGBTQ+ physicists [61], social capital considerations helped to formulate which alters to elicit and what kind of ties to explore in the interviews.

C. Social influence: Importance to spreading information and attitudes

The social influence framework links network structure with actor attributes through processes such as peer pressure, persuasion, and competition [38,62]. Many PER network studies focus on classroom networks with the expectation that students will transmit information and attitudes through their connections, and social influence is one framework to explore these mechanisms. Some investigations place primary importance on the cohesiveness of local network ties, while others examine the equivalence of tie structure, positing that people in similar social circumstances will be driven to act in similar ways [62].

Researchers interested in building community in student groups may find useful tools in the network literature on homophily [63], which is the tendency for ties to form and persist among similar individuals. The mechanisms behind this tendency are nuanced by preference, availability, and influence [38] (chap. 7), which can be studied qualitatively or quantitatively. The diffusion of ideas has also been explained using structural holes [58]—gaps in network connectivity mentioned in the previous subsection. These nuances of local network cohesion, and when it may be a benefit or a hindrance, might help to understand previous ambiguous network results in PER. For example, betweenness centrality, which quantifies being in a "broker" position between groups, sometimes has nonsignificant or even negative correlations with success measures ([26,64], and see commentary on this broader pattern in Ref. [65]). Unpacking the ties of high-betweenness students in terms of homophily mechanisms, or what ideas diffuse (or fail to) across their linking position, could help to clarify these ambiguous results.

In one example using the social influence framework, Lorenz *et al.* [66] review sorting effects that tend to homogenize friendship networks, then use widespread sampling and a longitudinal design to distinguish peer selection effects from students' educational expectations. Beyond classroom content, physics education researchers might find this framework valuable to study topics like the cohesiveness of departmental networks, looking at heterogeneity of alters, density of ties, or network fragmentation of students or faculty. To study how teaching reform spreads through faculty, the social influence perspective could pair very fruitfully with mapping faculty networks [67] to identify and follow change agents.

D. Other frameworks

A full survey of all the theoretical frameworks used—or useful—in SNA would be impossible, because the fundamental orientation of each application field influences what concepts are seen as sensible or relevant. For example, those coming from mathematical fields may focus on theory as meaning very specifically graph theory [68,69] and not the interpretive frameworks discussed above.

Organizational research has its own typology of concerns reviewed by Borgatti and Foster [70] or Borgatti and Ofem [71] have laid out possible lines of study from an educational-organizational perspective.

Because of this great diversity, our goal is not to argue for one theoretical framework over another but to advocate for the importance of using some framework to guide study design. Clarity about study goals and theoretical constructs is key to designing valid data collection. As we discuss below, the wording of prompts to elicit connections can affect the size and membership of the network, even for questions that seem closely related [72]. For researchers, the key questions are as follows: Why do you think connections between people are important in this setting? What do you hope to understand better by mapping those connections? Each of the frameworks above proposes different answers and defines a different space to explore.

IV. METHODOLOGY: HOW DO YOU INTEND TO STUDY THE NETWORK?

Most methods used for network data collection are used in other areas of PER as well. However, network-specific issues arise in collecting usable data and exploiting the relational perspective in analysis, as well as the unique tool of sociograms. We highlight key results here, beginning with a discussion of the different strengths of qualitative, quantitative, and mixed-methods designs.

A. Research approaches

1. Quantitative designs

SNA was rooted in quantitative sociology [1], and in PER, this has often been supplemented by complex network studies taking an algorithmic viewpoint on analysis [73]. For the purposes of this paper, a quantitative approach is characterized by the use of mathematical tools to map networks, measure their properties, or describe the position of nodes [74,75].

This orientation is common in whole-network studies and can be used in egocentric studies as well: for example, to survey the size, homogeneity, level of resource access, or other network traits for a population of interest. The work of Lorenz *et al.* referenced above [66] is one example, and McCarty [9] argues for the use of ego network structural measures to distinguish socialization patterns. If an appropriate sampling strategy is used, statistical inference tools can be used much more straightforwardly for ego networks than for whole networks, where the interdependence of the observations requires special methods [76]. Perry *et al.* [38] (chap. 3) give more guidance on egocentric network sampling concerns.

One decision in egocentric calculations, which does not appear in whole-network studies, is whether to include or remove the central node—the ego—for structural measures like density. An example is Wu *et al.*'s work [19] where physics lab teaching assistants (TAs) were the focus of the network, with students represented at the group level. Retaining the ego (TA) allowed for comparing levels of TA-group interaction between lab curricula. If the focus was instead on levels of student-student talk in different implementations, it might make more sense to subtract instructor ties before analyzing the remaining links. This question is significant for egocentric analysis and reporting because ego-to-alter ties will by definition be a substantial fraction of the network. In general, McCarty and Wutitch [77] argue for removing the ego if the goal is to study network-on-ego effects and keeping it for research that focuses on ego-on-network effects.

2. Qualitative designs

Qualitative designs can use many approaches toward inquiry (e.g., ethnography, narrative analysis, or phenomenography) but are united by the importance they place on "the understanding of meaning" [8] and the nuances of lived reality. Though qualitative network methods are rare in PER, they are well developed in other fields. Hollstein [8] recommends qualitative analyses for probing the mechanisms or dynamics behind observed network structure, as well as for validating or understanding other results. Crossley and Edwards [11] expand on the theme of mechanisms, arguing that individual network results are cases that do not generalize but that qualitative methods allow researchers to identify and explore broader mechanisms.

Qualitative methods are an essential precursor to many larger-scale quantitative studies and are an especially strong choice when the network dynamics are not well understood. However, they are also the primary means to focus on the nuances of network members' social worlds: the subjective meaning of relationships and how they influence participants [7]. Because of this sensitivity to nuance, qualitative approaches are especially valuable for understanding multiplex ties or for exploring sensitive topics. In a physics context, this might mean mapping the ties of support and capital that students need over their degree program or examining the inclusion and exclusion dynamics of study groups in the department. Understanding these processes or tendencies is key to tease apart the behavior of complex systems, such as classrooms or organizations, where simple causal claims are rarely possible.

To read more in this area, Hollstein [8] gives an overview of recommendations with many examples, primarily using grounded theory or ethnography. Another excellent introduction is work by Nimmon and Atherley [7], directed at health professions education researchers and with many parallels in PER. Their "research onion" diagram outlines many study design decisions that are important to document and report such as theoretical frameworks, methodological choices, time dimension, and type(s) of data collected.

3. Mixed-methods designs

Mixed-methods social network analysis (MMSNA) has received growing attention in recent years. Froehlich *et al.* [12] define MMSNA as "any SNA study drawing from both qualitative and quantitative data or using qualitative and quantitative methods of analysis," where those methods are "thoughtfully integrated." Edwards [75] argues that mixed methods combine the strengths of quantitative SNA for systematic and precise mapping with the nuance of qualitative tools for understanding what that structure actually means. She discusses broad strategies that may be useful, such as using quantitative and qualitative approaches in sequence to focus the analysis. In one example, Martínez *et al.* [42] collected a large body of data from a computer-supported collaborative learning environment and used quantitative network analysis to highlight groups of students for more in-depth qualitative analysis. In another example, Atherley *et al.* [51] found statistically significant shifts in the types of support network alters named over time by their student participants, then returned to the qualitative interview data to interpret and explain these shifts.

Looking to future studies, Edwards [75] notes that mixed methods are especially powerful for understanding context and change. In PER, this could be at the level of an individual student or a department/program and could take a whole-network or egocentric approach depending on the research questions. Because network objects inherently combine both structure and content, a blend of methods that addresses both at once can be very powerful, allowing a rich view of the mechanisms driving complex social systems [11,75].

To read more in this area, the overview by Edwards [75] is a good starting point. Many examples of specific method combinations are given there as well as in Crossley and Edwards [11] and Froehlich *et al.* [12], which lays out critical questions about why methods are being mixed and what to report.

B. Data collection and analysis

1. Research approach influence

Quantitative data collection methods include questionnaires about connections between nodes, observations, or using digital traces such as forum posting logs to indicate ties. Quantitative approaches to SNA are usually connected to a sociocentric approach, but it is also possible to select nodes within a whole network to focus on as subjects of qualitative research [8].

Qualitative approaches involve an overlapping set of data collection methods: observations, interviewing, and collecting documents or archival material are all common [8]. If actual behavior is the focus of the study, observation may be the most accurate tool (though see Ref. [78] for notes on difficulties). If perceived networks are the most relevant, which is often the case in social support studies, then interviews or surveys may give more salient data.

In the mixed-methods realm, Froehlich [43] mapped MMSNA studies in education and found that they were dominated by a small cluster of methods. Studies tended to use surveys or semistructured interviews for data collection, followed by network visualization and/or calculating summary statistics. Froehlich's analysis also found that while data collection and analysis methods were generally reported in sufficient detail to classify, much less information was given about sampling procedures or data preparation. His visual map of method co-occurrence is a good resource to see what has been done and it highlights potentially underdeveloped areas.

In PER, most network studies use surveys, where one or more prompts are used (often accompanied by rosters of names) to solicit network ties from respondents. The survey is given to all members inside the predefined network boundary, and the resulting whole network (typically with some missing data) is analyzed. In egocentric SNA, the process of soliciting alters is called "name generation" and follow-up questions to collect alter traits or ties come from "name interpreter" questions. Both of these tasks often use surveys and interviews, and for interviews, there is growing use of participant-drawn sociograms.

Because of their importance, we will focus on survey and interview data collection below, with extra attention to egocentric issues and specific notes about sociograms. For observational designs, Marsden [78,79] notes key studies and issues to consider, and Wu *et al.* [19] give an example in a physics lab context.

2. Surveys and interviews for network data

Surveys have been a dominant data collection tool in SNA for many years [78–80]. Two considerations that are especially relevant for SNA studies are how memory can affect network representations and how the network is theorized and operationalized in the prompts.

Like all recall-based data collection, surveys are subject to memory biases, but they still show reasonable accuracy and fidelity for many research purposes. Early studies often limited name generators to a small number of responses, such as five, to limit participant burden. However, this can seriously distort network results, so it is not recommended ([79], though see [78] for sampling-based workarounds). Name generators with context, specific relationships, or recent time frames can aid recall. In general, people are better able to remember closer connections and core members of their networks [80,81]. If more tenuous connections are also important to the research question (often the case, see Ref. [56]), the core contacts may be helpful bases for follow-up prompts (e.g., "Are there any other members of that study group?").

Name interpreters raise the question of whether reality or the respondent's perception of reality are most important.

For example, when reporting more observable traits like demographic characteristics, the ego's accuracy is generally good. But reports of alters' attitudes or beliefs tend to be slanted toward projecting the ego's own values [79], and this should be noted when making claims based on those responses.

The wording of the name generator can substantially affect the network. One common division of generators is by type: role, exchange, or interaction [79,82]. Role relationships such as "close friends" or "people you discuss important matters with" have often been used in sociology-based network research. Exchange generators target more specific dimensions, like "who are all the people you work with on physics homework?" or "who would you ask for advice about going to graduate school?" Unless only a very specific setting or only a very rough idea of the network are desired, multiple name generators are probably necessary to span the ties of interest [78]. Questions might also include negative support ties, which are seldom studied but can be very significant [79,82]. Finally, interaction-based name generators have also been explored in sociology, often in the context of attempting to gather the entirety of a person's contacts (perhaps over some threshold, like 5 min) in a time frame. Interaction prompts are often used in PER studies, for example, giving students a roster and having them complete "I had a meaningful interaction with these people this week" [31].

To study support networks, van der Poel [83] advocates for exchange-oriented name generators. He argues that interaction networks often neglect content and importance of their contacts, role relations (e.g., friends) can vary in how each type of role matters to the person, and affective prompts (such as asking about closeness) can vary greatly in interpretation. The exchange approach does neglect currently dormant connections, so it may underestimate the full support available. In a study of various prompts for emotional, instrumental, and social support, van der Poel [83] found that 3–5 name generators could span most of the variance and role relationships in the sampled personal support networks. Other good resources to learn more about name generator choices are comparative work by Milardo [82] or methodological notes by Bidart and Charbonneau [84], who outline how they tailored a multistage name generator to their specific research questions.

To return to the broader issue of framing and wording, one critical finding is that role, exchange, and interaction generators all produce different networks and should generally not be used as proxies for each other. In a comparative study [82], interaction and exchange networks had uncorrelated sizes and did not have substantial overlap of members. In PER terms, having a robust in-class interaction network may not translate to having good access to help with homework. Answers to the earlier "big questions" in study design can help to carefully choose targets for data collection.

3. Sociograms as data

Sociograms are a common tool in network interviews, and a small but growing number of studies also use them in computer surveys with no interviewer present [85]. Sociograms are a visual cue that often provokes extra recall or detail from participants. At a deeper level, they can become a thinking tool for the participant, taking them from listing to reflecting and theorizing about their relationships [86].

Sociograms vary in shape and level of structure or formality. A popular design is to give participants predrawn concentric circles with the ego at the center and larger circles representing decreasing closeness [87]. Figure 3 shows an example design we used to collect data with Google Jamboards in a study of the professional support networks of women and LGBTQ+ physicists.

Sectors may be premarked for roles such as friends or coworkers [85,86], or the plotting space may be free of such divisions, or may even be a completely blank free-drawing area [88]. The level of structure influences the kind of data that is collected and what it is possible to do with it. Hollstein *et al.* [88] compared several sociogram designs and found that the concentric circles format was the most popular with participants. The free-mapping variant produced the most quirky data, with network members including dead people and pets. The authors caution that if researchers plan to compare networks, a standardized script for introducing and using the diagram is important because even a preprinted structure such as circles is still subject to varying interpretations.

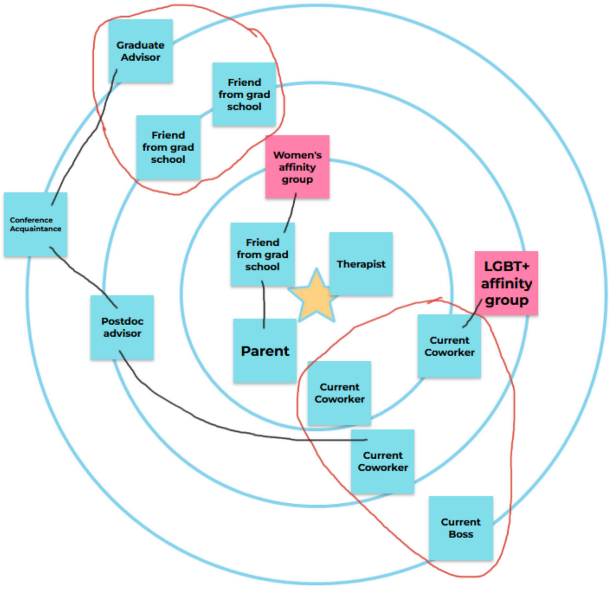

FIG. 3. Example sociogram a participant might construct during the interview. Blue sticky notes are for individuals and pink for groups. Names would typically be used by participants, but here are replaced by anonymous descriptors.

Ryan *et al.* [89] discuss other facets of visualizing networks in interviews. They found it to be an especially helpful tool to talk about dynamism and changing ties, which is often a struggle for survey-based quantitative network studies. However, they also found a few instances of participant discomfort, if people felt guilty about forgetting a contact or were uneasy at the status implied in ranking alters' distance from the center. Echoing some of Hollstein and collaborators' cautions, the researchers found that completion could be idiosyncratic, so detailed comparisons between sociograms should be made with care.

For practical considerations, Hogan *et al.* [90] introduce an interview method that combines survey-style name generation with placement on a sociogram. Their suggestions for marking alter-alter ties (used in Fig. 3) can greatly alleviate the response burden for participants, which otherwise increases dramatically as the number of alters grows [91]. Molina [92] has recommendations for question sequence to help recall of groups versus communities. Finally, if detailed knowledge of alter-alter tie structure is paramount, then a more traditional survey grid that requires explicitly evaluating every tie may be best, as visual mapping has some bias toward the most subjectively salient alters and ties [85]. As always, the nature of the tool affects the data collected, so researchers should consider in advance what is the most important to gather [89]. The power of visual sociograms can benefit many PER studies, especially with a qualitative or mixed-methods focus where the shared discussion space of the network can draw out additional nuance and detail.

C. Network visualization

Network data presents special opportunities and challenges when it comes to visualization. Molina *et al.* [92] review ways that network visualizations can contribute to data collection and analysis. Their discussion emphasizes how visuals can highlight patterns and raise questions for further investigation but need to be accurate. Work by Hogan *et al.* [90] has repopularized sociograms in data collection, especially as web-based tools become more robust. Tubaro *et al.* [86] discusses examples of visual methods at different data collection and analysis stages, and Rios-Aguilar and Deil-Amen [59] provide an interesting variant using anonymized roles of alters to show and discuss different patterns in students' social capital.

Molina *et al.* [92] find that most visualizations of personal networks are for exploratory purposes, but they can also be used for confirmatory analysis of conjectures (e.g., what network patterns would our hypotheses predict?), for model validation, or for *post hoc* analysis. Bidart *et al.* [93] developed a taxonomy of personal networks by visually sorting first, and then testing a decision tree of structural measures to capture the observed types. Representations can range from reproducing participants' own placement choices [51,86], to computer-generated layouts that show areas of closeness and interconnection [86,93], to intentional abstraction and rearrangement for the purpose of highlighting group ties or power relations [94,95].

Egocentric network studies with more than a few participants have their own set of challenges, as displaying many sociograms becomes visually overwhelming. One common

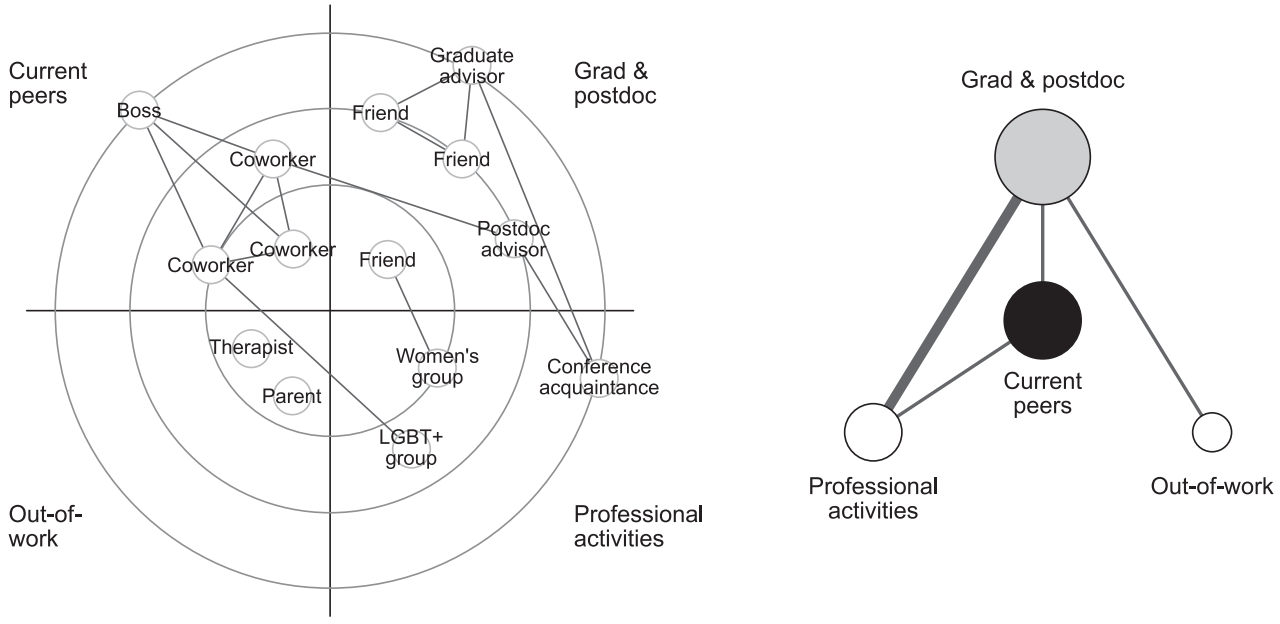

FIG. 4. Example of a personal network (Fig. 3) redrawn using quadrants for alter types (left) or using alter types to condense as suggested by Brandes *et al.* [95] (right). On the left, each circle indicates one node (person or group), and the larger concentric circles indicate decreasing closeness from the ego. On the right, circle size indicates the number of alters in that category, shading shows the density of connections within the category, and link thickness shows the relative density of ties between categories.

approach is to select examples to show key trends [20,51]. Alternately, Brandes *et al.* [95] develop a method for visually summarizing networks in studies where the alters can be divided into distinct classes (e.g., classmates, faculty, non-classmate peers, and family). By condensing information about these categories' sizes and connection density in a reduced graph, many networks can be compared to look for trends [92,95,96], or aggregate graphs can summarize and compare variability between ego groups of interest. Figure 4 uses Fig. 3 network to show examples of placing alters by category and a condensed graph using the method of Brandes *et al.* [95].

How to visualize networks and what information to highlight or suppress has been an evolving topic for the whole history of SNA [97], and the mathematical focus on large-graph visualizations has largely disjoint literature from the more sociological tradition of SNA [98,99]. Physics education researchers might find tools of interest in both spaces, but here we have focused on resources especially relevant for personal network analysis, as those are less known in PER. We also think that PER, as a field blending disciplines and methodological approaches, could add valuable insights to this area of network studies.

V. EXAMPLES FROM THE LITERATURE

Because of the dominance of whole-network and quantitative approaches in PER, we have drawn most of our examples in this paper from outside the field. Additionally, to illustrate theoretical frameworks or methods, we used many sources in the broader sociology literature beyond education. We thus want to end by returning the focus to educational contexts.

Table I collects all references from this paper that concern educational settings (physics or otherwise) and use one or more of egocentric network analysis, qualitative methods, or mixed methods. Below, we discuss four studies in more detail, particularly their problem of interest, their methods and use of theory, and how the network approach informed their results.

A. Qualitative egocentric study of Latina/o social capital

Qualitative egocentric studies are well suited to explore the nuances of personal situations and the mechanisms that may underlie larger network patterns. We chose Rios-Aguilar and Deil-Amen's paper [59] as an example because it is a fully qualitative study that uses the visual power of sociograms to illustrate and compare profiles uncovered by the analysis.

The paper uses a qualitative egocentric study of first-year Latina/o college students to understand the networks involved in their entry to college. The study pursued two research questions: (i) What are the patterns in Latina/o students' social ties during their transition into and through the first year in college, and (ii) What is the size of the network and the content of the exchanges between the Latina/o students and each network tie? Initial data were collected through 261 essays written by Latina/o students in a summer bridge program. Subsequently, 61 of the students participated in semistructured interviews, and the data collected through both methods were used to compose sociograms of students' networks.

The analysis proceeded from open coding, to generating ego networks using alter categories, to a second round of coding that incorporated network reflections. From this, four key network patterns emerged for discussion. The results highlighted the guidance Latina/o students received regarding what and where to go for college ("getting in") and the networks they mobilized in trying to find their place in college ("fitting in"). The paper goes beyond the idea of fitting in to also examine the networks students build to support their trajectories after college, from students to professionals. An interesting finding is that during college, Latina/o students do not build a network that can support this transition, and heavily rely on their "getting in" and "fitting in" networks, even when these lacked the resources to provide career guidance.

The findings of the paper have implications for future support and diversity, equity, and incusion efforts. The challenge is not only to enroll more students from diverse backgrounds and with minoritized identities: how those students get in and fit in is important but also how/if those processes connect to their careers after college. The combination of methods allowed researchers to explore students' social capital around their college aspirations and how support programs might supplement that capital in measurable and meaningful ways.

Several aspects of the presentation might also be useful for PER researchers interested in egocentric SNA. One idea is using roles instead of names to represent the alters and including multiple egos in one sociogram to visually contrast how egos build their networks. Abstracting alters into categories (e.g., family, clubs, and organizations) in the first round of coding made it possible to find broad trends of roles that were present or absent in networks. It also facilitated placing discovered network patterns on the same sociogram at once, providing some of the "big picture" overview that a whole-network study might give.

Another interesting choice was to select the diagrams and ties that were relevant in different contexts, allowing comparison not only among egos but also for the same egos in different moments or for different types of ties. The detail of the data allowed the researchers to contrast network patterns between the high school, college, and professionally relevant sets of ties. Both the qualitative and egocentric elements were essential to the analysis, where a whole-network approach did not match the study population, and a quantitative design would have preimposed researcher categories rather than starting from the students' experiences.

TABLE I. Education network studies referenced in this paper that use egocentric, qualitative, or mixed-methods designs. Since mixed-methods studies may have a completely quantitative network component, we have flagged qualitative network methods specifically.

Authors (year)	Title	Egocentric	Qualitative networks	Mixed methods
A. E. N. Atherley, L. Nimmon, P. W. Teunissen, D. Dolmans, I. Hegazi, and W. Hu (2021)	Students' social networks are diverse, dynamic and deliberate when transitioning to clinical training [51]	Y	Y	Y
R. M. Goertzen, E. Brewe, and L. Kramer (2013)	Expanded markers of success in introductory university physics [20]	Y	Y	
C. Rios-Aguilar and R. Deil-Amen (2012)	Beyond getting in and fitting in: An examination of social networks and professionally relevant social capital among Latina/o university students [59]	Y	Y	
L. Nimmon and A. Atherley (2022)	Qualitative ego networks in health professions education: Capturing the self in relation to others [7]	Y	Y	
M. P. Skahill (2002)	The role of social support network in college persistence among freshman students [52]	Y		
G. Lorenz, Z. Boda, Z. Salikutluk, and M. Jansen (2020)	Social influence or selection? Peer effects on the development of adolescents' educational expectations in Germany [66]	Y		
O. Casquero, R. Ovelar, J. Romo, M. Benito, and M. Alberdi (2016)	Students' personal networks in virtual and personal learning environments: A case study in higher education using learning analytics approach [96]	Y		
D. G. Wu, A. B. Heim, M. Sundstrom, C. Walsh, and N. G. Holmes (2022)	Instructor interactions in traditional and nontraditional labs [19]	Y		
S. Dawson (2010)	'Seeing' the learning community: An exploration of the development of a resource for monitoring online student networking [41]	Y		
M. de Laat, V. Lally, L. Lipponen, and R.-J. Simons (2007)	Investigating patterns of interaction in networked learning and computer-supported collaborative learning: A role for Social Network Analysis [44]		Y	Y
J. Pulgar, C. Candia, and P. M. Leonardi (2020)	Social networks and academic performance in physics: Undergraduate cooperation enhances ill-structured problem elaboration and inhibits well-structured problem solving [21]			Y
A. J. Gonsalves and H. R. Chestnutt (2020)	Networks of support: Investigating a counterspace that provides identity resources for minoritized students in postsecondary physics [30]			Y
A. Martínez, Y. Dimitriadis, B. Rubia, E. Gómez, and P. de la Fuente (2003)	Combining qualitative evaluation and social network analysis for the study of classroom social interactions [42]			Y

B. Qualitative whole-network study of distance learning students

Although our paper focuses on egocentric network analysis, qualitative and mixed-methods designs can also bring new perspectives to whole networks. This is common in anthropology, but much less used in science education. We chose an analysis by de Laat *et al.* [44] as a fairly uncommon case of qualitative whole-network analysis in a mixed-methods study, including a good discussion of how network analysis can be used with other methods to triangulate results.

Network analysis appears in many studies of online or distance learning, often drawing on frameworks from computer-supported collaborative learning (CSCL; [15]). The study by de Laat *et al.* focuses on a networked learning community of master's students in an E-learning program [44]. The researchers' goal was to discuss how to use SNA to study computer-supported collaborative learning and to

add a layer of relational analysis to their existing case study data. The larger project used content analysis and interviews to describe teaching and learning in a distance learning course. Content analysis was used on a sample of the online messages from a 10-week workshop period to characterize learning and tutoring activities. Messages were coded under two classifications: one for types of "on the task" work by students, and one focused on tutoring activities "around the task." This content analysis was used to extract patterns, and then critical event recall interviews were conducted with participants to probe those patterns and the context in which they arose. Then, qualitative analysis was used on the whole learning community network, using the time change in measures such as network density and centralization to think about the whole-class context for individual results from the earlier analyses.

The authors used analytic frameworks from CSCL to guide their content analysis. This use of theory structured the interaction patterns they looked for. These coded interactions were then interpreted using time-sequenced network diagrams to understand how the learning community evolved at the whole-class level. The earlier stages of the analysis identified patterns and participants' explanations of their learning processes. Network analysis added a view of how participation changed over time, with people becoming more central or peripheral at different stages of the 10-week course project. Combining network with message and interview data also highlighted that students could be central for different reasons (e.g., debating and putting forward new ideas vs managing group activity).

Qualitative analysis can be difficult to perform on larger networks, but many departments will have courses of a size that would fit well with this kind of design. With hybrid and online courses increasingly common, the diverse CSCL network literature [15] has many examples to offer physics education researchers, including some egocentric cases [41,96].

C. Mixed-methods egocentric study of medical students

Atherley *et al.* used mixed-methods egocentric analysis to study support networks in medical students transitioning into clinical clerkships [51]. These transition periods are significant parts of medical education and professionalization but are understudied from a social perspective. We chose this paper as an example of a mixed-methods study where both quantitative and qualitative tools were used to interpret the networks.

The research questions were as follows: (i) Who are in the social networks of undergraduate students transitioning to the clinical environment? (ii) To what extent do undergraduate students' networks change as they transition to the clinical environment? What are the mechanisms behind these changes? Theoretically, the authors drew on social constructivism, social support, and communities of practice. The SNA data were collected by interviews, including participant sociogram construction, at the beginning and 4-month points of the clerkships. Interviews solicited the name, role, gender, and polarity (positive or negative interactions) of everyone who impacted the participant's transition. The analysis compared network size and role composition between time points and found that the networks did not significantly grow, but the distribution of roles changed, with ties shifting away from nurses and near-peers (students in other years) and toward doctors and peers (students in the same cohort).

These patterns were explored through inductive thematic analysis of the transcripts, sociograms, and videos recorded from interviews. The qualitative analysis shed light on the mechanisms behind the changes in networks, such as the persistence of ties to doctors who integrated students into the clinical team or the time it took to build trust in peers and start sharing professional norms. For physics education researchers, this work gives a mixed-methods example where the network framing was integrated at all stages of data collection, analysis, and interpretation of results.

D. Qualitative egocentric study of women and LGBTQ+ physicists

As a final example, we outline our in-progress work as a case of using qualitative egocentric networks in PER. The project studies the professional support networks of women and LGBTQ+ (lesbian, gay, bisexual, transgender, and queer) physicists and astronomers in the United States. The research questions are as follows: (i) How are the professional support networks of women and gender and sexual minorities (GSM) in physics characterized in terms of size and density, the type of ties in the network, and the structure of communities, as well as the presence and integration of advocacy connections? (ii) How satisfied are women and GSM in physics with their career trajectories and current job situations? What network patterns, if any, are associated with higher satisfaction and a sense of professional identity? (iii) What similarities and differences exist when comparing academia, industry, and government job sectors?

Participants were women and LGBTQ+ persons who hold a Ph.D. in physics or astronomy, currently working in the United States in academia, government, or industry sectors. They were recruited by a questionnaire posted on social media, shared on listservs, and sent to people within the researchers' networks, with further snowball sampling once interviews started. Extensive recruitment was needed to reach our target of 100 participants, with at least one third in each job sector and at least half of participants in each of the main criteria (identifying as a woman or as LGBTQ+).

Interviews were semistructured, with both social support and social capital lenses used to frame the questions. Participants constructed a sociogram during the interview using a Google Jamboard, eventually adjusting the sticky

notes to cluster people or groups who know each other and drawing lines to connect them (Fig. 3).

The analysis of the interviews and sociograms is in progress. Initial results speak to the problems of physics' "identity neutral" values for graduate students from gender or sexual minorities [61] and the nuanced role of instrumental support in navigating workplaces [100], while other aspects such as the comparison between work sectors are in progress. One issue to note is the trade-off in user accessibility and data accessibility: we chose Google Jamboard to draw sociograms for ease of use by our participants, but more specialized software such as VennMaker or Network Canvas would not require manual transcription of networks after the fact. The main focus of this study is qualitative, but researchers needing more standardized quantitative measurements should consider this trade-off carefully.

VI. CONCLUSIONS

Most network analyses in PER use quantitative methods and focus on network function and structure or student persistence in physics. We argue that PER would benefit from—and can contribute to—the wider range of tools, frameworks, and research questions found in educational network research. In particular, egocentric approaches offer many options for extending beyond the boundaries of a single course or for considering widely separated individuals through network perspectives. Qualitative or mixed-methods approaches allow additional depth and nuance in understanding the mechanisms underlying network ties, which are generally invisible in quantitative studies. In this review, we have tried to highlight both challenges and areas of potential, as well as provide many resources and examples to help researchers explore further.

We organized the paper around key questions that arguably could benefit any network study, but which we found especially relevant in mapping out a methodologically unfamiliar space. The network literature spreads over many disciplinary journals, so we prioritized key results and reviews over closeness to physics. We return now to our "big questions" as a way to organize suggestions for new directions that PER might take with network analysis, either to enrich physics education research or to enrich network analysis with new PER contributions.

A. Conceptualizing: What interests you about the network?

Common dimensions of study for egocentric networks include structure, function, tie strength, and content of the network. Investigations of interest to PER might include:

Structure: What are the network formation processes of physics majors over their first year (e.g., connecting majors in large introductory courses, forming ties to the larger department community)? How do these networks relate to students' persistence or other outcomes?

Function: What physics-relevant resources do students have access to in their personal networks (e.g., math or programming knowledge, mentors who could write recommendation letters, research group placement opportunities)? Are there systematic gaps that could be addressed by department initiatives?

Strength: What do strong vs weak ties look like among physics students? Most PER studies have used unweighted ties, so investigation of Granovetter's "strength of weak ties" mechanisms in this disciplinary context is an open question. How do such ties appear among students targeted by support initiatives like bridge programs?

Content: What do students know about their study groups' physics knowledge? This could qualitatively probe recent results about biases in peer recognition networks [101]. Alternately, sessions of videotaped student work where sensemaking or conceptual change is observed could also be examined by a network lens, either using the video data or with parallel network instruments.

B. Theoretical framework: Why do you think the network is important?

In Sec. III, we reviewed three theoretical frameworks commonly used in egocentric SNA that might be of relevance to PER. These or others can be used to design clearer or more targeted probes of the network. Beyond that, however, we see a number of places where PER could uniquely contribute by combining network approaches with "locally sourced" theory. For example, frameworks such as critical physics identity [48] note the importance of recognition from others and relational resources, and qualitative or mixed-methods network designs could pair naturally with studies using this framework. The communities of practice framework has been very fruitful in our subfield but is rarely combined with formal network approaches. This seems to be more broadly true—some work in organizational research has dealt with combining the two [102], but in general, this is an underdeveloped crossover where the expertise of physics education researchers could greatly contribute. Further possibilities remain to be explored; for example, could the spread of productive (or unproductive) resources for learning physics concepts and practices be observed in a class network? Borgatti and Halgin's distinction [50] about networks as cause vs networks as effect may be a good starting place for these discussions.

C. Methodology: How do you intend to study the network?

Section IV discussed methodology in network studies through several foci: the interaction with research approach (quantitative, qualitative, or mixed methods), concerns for data collection and analysis, and the particular role of visualization in network studies. Rather than strictly

following this division here, we include several ideas under the methodological theme:

Focus on smaller settings or select populations: We appreciate and agree with a reviewer's suggestion that qualitative and/or egocentric approaches could be very useful for researchers whose student populations are smaller—for example, those focused on upper-division physics courses or working at minority-serving institutions like historically Black colleges and universities.

Egocentric career studies: Postgraduate working physicists are a very poorly bounded population for a whole-network study but very approachable for personal network analysis. For example, studies with industry professionals have given important insights into the skills actually needed by physics graduates [103], and additional studies could explore the networks used to find and navigate such jobs. Our own in-progress work has focused on one demographic area for professional support networks, but many physics departments struggle to connect their students with non-academic career options, so this is an area where network researchers could give much-needed insights.

Triangulation with other data: Several of the studies in our overview of recent work reported correlations between students' network positions and their performance in physics courses. These correlations are ripe for more qualitative probing—for example, do students with low (or high) conceptual pretest scores engage in different networking behavior, are they preemptively recognized by their classmates as knowledgeable (or not), or something else? How do these nuances differ for students who do not follow the correlation (e.g., those with high centrality but low pretest scores)? Alternately, personal networks or qualitative interviews could be used to triangulate with observational network studies [19] to validate or expand on their patterns. Attitudinal or sense of belonging measures [104] might pair well with social influence frameworks or to judge the effectiveness of community-building interventions.

Search for mechanisms: Most network studies in PER rely on one or two time points as "snapshots," with rare examples of more frequent sampling [73]. Qualitative or especially mixed-methods tools have excellent potential to animate these snapshots and search for mechanisms. For example, how do students describe their choices of who to work with, which produce evolving gender segregation [73]? How do students form study groups in their introductory courses and do in-class network surveys accurately represent these configurations?

Finally, we believe that PER, as a multidisciplinary and multimethod field, can give new perspectives to the wider network analysis community. For example, how to visualize social networks, and what information is best to highlight, is an ongoing discussion with a fairly *ad hoc* history [97]. Physics is a representationally rich field, which has produced iconic diagrams (e.g., Hertzsprung-Russell in astronomy or Feynman in quantum physics) to distill complex phenomena into a visual essence. What insights can we give in this area?

D. Metarecommendations

The suggestions above are obviously not exhaustive but meant to inspire a sense of the possibilities. We end with metarecommendations for those who might want to expand into new types of network analyses:

- Answer the "big questions" posed in Sec. I not just during study design but when reporting results. Because there are so many possible orientations toward networks, being explicit helps other researchers to understand claims and highlight gaps for future study.
- Decide early how much standardized or quantified comparison between networks is desired. For detailed quantitative study, the sequence and wording of prompts should be as uniform as possible [88]. However, the freedom allowed by less-structured interview methods might be a higher priority depending on the research questions.
- Be clear and descriptive about methodological choices. In mixed-methods network studies, the purpose of the "mixing" is not always clear [12], and post-data-collection processing is often underdescribed. Studies using less-common tools like essays [59] to uncover network information can contribute methodologically by documenting how they go from the original form of the data to encode network ties.
- Push for theory building, explanatory, and intervention work. Like other educational areas where SNA is a relatively new tool [15], most PER network studies to date focus on visualizing or analyzing networks, often descriptively. Much more work on inference, modeling, simulating, probing mechanisms, and testing interventions remains to be done.

Social network analysis now has an established research presence in PER, so this is an excellent time to expand our methodological base and contribute to wider network studies conversations. We look forward to seeing how these tools can be applied to the problems of teaching, learning, and practicing physics.

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