Supporting Sustainability: Teachers' Advice Networks and Ambitious Instructional Reform
Author(s): Cynthia E. Coburn, Jennifer L. Russell, Julia Heath Kaufman, and Mary Kay Stein
Reviewed work(s):
Source: *American Journal of Education*, Vol. 119, No. 1 (November 2012), pp. 137-182
Published by: The University of Chicago Press
Stable URL: http://www.jstor.org/stable/10.1086/667699

Supporting Sustainability: Teachers' Advice Networks and Ambitious Instructional Reform

CYNTHIA E. COBURN
University of California, Berkeley

JENNIFER L. RUSSELL
University of Pittsburgh

JULIA HEATH KAUFMAN
University of Pittsburgh and Carnegie Mellon University

MARY KAY STEIN
University of Pittsburgh

Scaling up instructional improvement remains a central challenge for school systems. While existing research suggests that teachers' social networks play a crucial role, we know little about what dimensions of teachers' social networks matter for sustainability. Drawing from a longitudinal study of the scale-up of mathematics reform, we use qualitative social network analysis and qualitative comparative analysis (QCA) to investigate the relationship between teachers' social networks and sustainability. Teachers' social networks in the first 2 years of the initiative influenced their ability to sustain reform-related instructional approaches after supports for reform were withdrawn. Social networks with combinations of strong ties, high-depth interaction, and high expertise enabled teachers to adjust instruction to new conditions while maintaining the core pedagogical approach. This research contributes to our understanding of the dynamics of sustainability and to social network theory and research.

Scaling up instructional improvement efforts remains one of the central challenges facing urban school systems. In the past decade, no longer content to have pockets of success, school districts across the country began to develop systems for fostering instructional improvement among teachers and schools throughout the district (Hightower et al. 2002). Yet, while some of these ex-

Electronically published September 18, 2012
American Journal of Education 119 (November 2012)

0195-6744/2012/11901-0006$10.00

periments in widespread instructional reform have begun to yield success (Elmore and Burney 1999; Marsh et al. 2005; Snipes et al. 2002), sustainability remains a persistent challenge (Coburn 2003). School district priorities almost inevitably change over time. Resources to support initiatives run their course. Schools and teachers that successfully implement instructional reforms find it difficult to sustain them in the face of changing priorities, limited resources, and competing demands (Berends et al. 2002; Hargreaves and Fink 2000; Mac Iver et al. 2003).

Many studies have pointed to the nature and quality of teachers' professional relations with one another as a key contributor to their ability to sustain instructional reform (Cooper et al. 1998; Gersten et al. 2000; Klingner et al. 1999; McLaughlin and Mitra 2001). This research provides evidence that teachers' professional interactions enable them to learn from one another (Gersten et al. 2000; Klingner et al. 1999), deepen their practice, and coordinate action (McLaughlin and Mitra 2001). Yet, while we know teachers' social relations are important, few studies measure interaction directly or in much detail. Thus, we know little about what dimensions of teachers' social relations matter for sustainability.

Researchers using social network theory and analysis have developed conceptual and methodological tools for investigating social relations with more precision. They provide evidence that several dimensions of social networks, including tie strength, level of expertise, and depth of interaction, play an important role in such relevant outcomes as diffusion of innovation, transfer of complex information, and reform implementation (Frank et al. 2004; Hansen

---

CYNTHIA E. COBURN is associate professor of policy, organizations, measurement, and evaluation at the Graduate School of Education, University of California, Berkeley. She studies the relationship between policy and practice in urban schools, school district evidence use, and teachers' social networks. JENNIFER L. RUSSELL is assistant professor of learning science and policy at the School of Education and research scientist at the Learning Research and Development Center, both at the University of Pittsburgh. She uses the conceptual tools of organizational sociology to examine the relationship between policy shifts and the organization of public schooling. JULIA HEATH KAUFMAN is a research associate at the University of Pittsburgh and a research scientist at the Open Learning Initiative at Carnegie Mellon University. Her research focuses on how instructional policies and programs can support high-quality teaching and learning in schools. MARY KAY STEIN holds a joint appointment at the University of Pittsburgh as professor of learning sciences and policy and senior scientist at the Learning Research and Development Center. Her research focuses on mathematics teaching and learning in classrooms and the ways in which policy and organizational conditions shape teachers' practice.

1999; Obstfeld 2005; Penuel et al. 2009; Reagans and McEvily 2003). But, because this research tends to investigate a single dimension at a time, we know little about how, if at all, these dimensions interact. Furthermore, this research has largely focused on adoption and implementation. To date, there is no research that investigates the relationship between social networks and sustainability.

Here we use the tools of qualitative social network analysis and qualitative comparative analysis (QCA) to investigate the relationship between teachers' social networks and sustainability. We draw on data from a study of one district's attempt to develop teachers' capacities to teach mathematics in a more student-centered, conceptually-based manner, using an innovative mathematics curriculum called *Investigations in Number, Data, and Space*. After spending 2 years providing extensive opportunities for teachers to learn this new approach, including professional development, school-based mathematics coaching, and time for teachers to look at data and co-plan instruction, the district shifted its priorities and withdrew these supports. In the third year of the initiative, teachers were faced with sustaining new instructional strategies in the absence of formal support. Just over half of the teachers in our sample were able to do so. We argue that the nature of teachers' social networks in the first 2 years of the initiative played an important role in whether and how teachers sustained reform-related instructional approaches in year 3. More specifically, social networks with a combination of a high level of expertise, strong ties, and high-depth interaction focused on substantive issues related to mathematics and pedagogy sufficient to support sustainability. Social networks with this combination of conditions enabled teachers to develop a strong enough understanding and flexible enough enactment of reform-related strategies that they were able to adjust to new conditions in year 3 while maintaining the underlying pedagogical approach. After elucidating how these different dimensions of social networks worked together to support sustainability, we close with contributions to research on sustainability and social networks.

Social Networks and Sustainability

Sustainability is one of the central challenges for instructional improvement efforts. Several decades of research document the challenges of maintaining new instructional approaches in the face of changing priorities, competing initiatives, and shifting conditions in schools and districts (Coburn 2003; Cuban 1993; Datnow et al. 2002; Tyack and Cuban 1995). Yet, as important as this issue is, existing research on sustainability is limited. Most studies investigate new initiatives at their start. Few researchers continue to collect data after the initial infusion of resources and support is withdrawn (Coburn 2003; Gersten et al. 2000; Hargreaves and Goodson 2006). Thus, they are not able to capture sustainability, defined here as the degree to which teachers use reform-related practices in high-quality ways after support for these practices has dissipated. Other studies of sustainability initiate investigation after support for implementation has ended. While these studies are well suited for capturing the degree to which an instructional approach is sustained, they typically rely on retrospective, self-reported data to understand implementation. Because retrospective data are often very general and can be smoothed by the passage of time, this approach can provide only limited insight into what happens during implementation that fosters sustainability.

A modest number of studies are designed to investigate the dynamics of implementation and sustainability in real time. These studies have mainly focused on identifying a list of factors that appear to contribute to teachers' abilities to maintain instructional reform over time, including effective and stable school leadership (Berends et al. 2002; Bryk et al. 2010; Datnow et al. 2002; Gersten et al. 2000; Klingner et al. 1999), teachers' social relations (Bryk et al. 2010; Datnow et al. 2002; Hargreaves and Goodson 2006; Klingner et al. 1999; McLaughlin and Mitra 2001), supportive or at least not unsupportive district climate (Berends et al. 2002; Coburn 2003; McLaughlin and Mitra 2001), sufficient resources (Klingner et al. 1999; McLaughlin and Mitra 2001), and strong understanding of the reform on the part of teachers (Coburn 2003; Klingner et al. 1999; McLaughlin and Mitra 2001). But few studies investigate any given factor related to sustainability in any detail. Thus, while these studies play an important role in identifying key factors that may be involved, it is time for more in-depth studies of when, why, and how specific factors contribute to sustainability. Here, we contribute to the nascent literature on sustainability by conducting an in-depth investigation of the relationship between one factor identified in the literature—teachers' social relations—and teachers' ability to sustain instructional reform over time.

Teachers' Social Relations

Existing research that attends to the role of teachers' social relations in sustainability finds that teachers' interactions with others are important because they provide access to knowledge, feedback, and social support that enables teachers to deepen their understanding and enactment of new approaches (Cooper et al. 1998; Gersten et al. 2000; McLaughlin and Mitra 2001). In turn, teachers with at least a moderate level of implementation or deep understanding are more likely to sustain those reforms (Gersten et al. 2000; Klingner et al. 1999; McLaughlin and Mitra 2001), likely because deep understanding enables teachers to make principled, practical adjustments to new students, conditions, and subject matter in ways that maintain the underlying pedagogical approach (Coburn 2003; McLaughlin and Mitra 2001). Strong relationships further support sustainability by fostering common approaches and reinforcing norms that coordinate action by helping teachers move in the same direction (Hargreaves and Goodson 2006; McLaughlin and Mitra 2001). In the absence of such social support, teachers feel isolated (Klingner et al. 1999; McLaughlin and Mitra 2001) and have difficulty navigating changing demands (Hargreaves and Goodson 2006), threatening sustainability.

However, existing research on teachers' social relations and sustainability suffers from several limitations. Most studies fail to measure teachers' social relations with much precision. Some studies discuss teachers' social resources quite generally, using many different terms (e.g., "professional communities," "peer support," or "communities of practice," to name a few) and providing little information about how they measured teachers' social relations at all (e.g., Gersten et al. 2000; Hargreaves and Goodson 2006). Others employ careful measurement strategies but do not measure the nature of teachers' interaction directly. Instead these studies rely on teachers' perceptions of the nature of collaboration or level of supportiveness of colleagues in the school as a whole (e.g., Bryk et al. 2010; Klingner et al. 1999; Louis and Marks 1998). This approach does not attend to who teachers are actually interacting with and the nature and quality of that interaction. Furthermore, existing studies tend to assume in advance the locus of professional community, focusing on the school as the unit of analysis or on formal organizational structures like grade-level groups or departments (e.g., Bryk et al. 2010; Louis and Marks 1998; McLaughlin and Mitra 2001). Yet we know that teachers are often embedded in a network of relations that span multiple subgroups and include individuals both inside and outside of school boundaries (Bidwell and Yasumoto 1999; Coburn 2001; Coburn et al. 2012; Penuel et al. 2009; Yasumoto et al. 2001). The nature of teachers' social relations can also vary greatly within a school or even a grade level (Coburn et al. 2012; Penuel et al. 2009). Consequently, there is still much to learn about just what it is about teachers' social relations that matters for their ability to sustain new instructional strategies over time.

Social Networks Theory and Analysis

To address these issues, we draw theoretically and methodologically from social network theory. Social network theory is an approach for understanding how an individual's or organization's location in a web of social relations enables and constrains a range of organizational and individual processes and outcomes. Rather than explaining social phenomenon by investigating attributes of individuals or organizations, social network theory shifts the angle of vision to the system of social relations within which action is embedded. It then investigates how the configuration of these relations matters for a range of important outcomes (Borgatti and Ofem 2010; Kilduff and Brass 2010). Social network analysis is a methodological approach developed to investigate the nature and configuration of these social relations. It involves systematically mapping patterns of relationships by identifying the ties between individuals (or organizations), the features of those ties, and how ties between dyads interconnect to form a system of relations as a whole (Valente 1995).

To date, we know of no studies that use social network theory and analysis to investigate the relationship between social relations and sustainability. However, there are studies on the relationship between social networks and reform implementation from which we can draw guidance for building our conceptual framework. Researchers have identified a number of dimensions of social networks that influence diffusion of innovation, knowledge transfer, and implementation. Here, we focus on three: tie strength, access to expertise, and depth of interaction.

Tie strength.—There is evidence that strong ties—those characterized, variably, by high frequency, social closeness, or a combination of the two—are beneficial for transfer of fine-grained or tacit knowledge, collaboration, or sustained problem solving (see Obstfeld [2005] for a review). To the extent that sustainability requires substantial reform-related knowledge (Gersten et al. 2000; Klingner et al. 1999; McLaughlin and Mitra 2001), it is possible that strong ties may be important for sustainability as well.

Level of expertise.—While most social network research has focused on structural and relational aspects of networks, there is a growing interest in the nature of the "competencies and resources" that are available at the nodes (Adler and Kwon 2002, 26). Scholars reason that if social networks are a means to access the resources that are available by virtue of one's position in a network of social relations (Adler and Kwon 2002), then it is important to attend to the nature of those resources as well. Indeed, research outside of education has shown that social networks differ markedly in the level and diversity of resources—information, contacts, people with power—to which they afford access (Lin 2000). Research in education has mainly focused on the degree to which social networks create access to expertise. For example, a series of studies by Frank and Penuel finds that the mean level of reform-specific expertise in one's subgroup and the other subgroups with which one interacts predicts implementation for reform efforts ranging from use of computers in the classroom (Frank et al. 2004) to complex literacy reform (Penuel et al. 2010). These scholars suggest that reform-specific expertise in one's network provides access to real-time support that assists a teacher in strengthening enactment. Given research on the role of strong enactment in sustainability (Gersten et al. 2000; Klingner et al. 1999), access to expertise may also foster a teacher's ability to sustain this enactment after supports for implementation are withdrawn.

Depth of interaction.—Although social network theory is premised on the notion that resources "flow" through interpersonal connections, few scholars directly investigate what transpires in social network transactions. Instead they infer the nature of interaction from the structure of the ties or the attributes of the nodes (Borgatti and Foster 2003). This has led to a range of competing theories about the mechanism by which social networks contribute to valued outcomes (Borgatti and Foster 2003; Kilduff and Brass 2010). Some scholars argue that social networks influence outcomes via peer pressure and social control (Centola 2010; Coleman 1988). Others argue that they facilitate change by creating conditions for individuals and groups to learn from and with one another (Hansen 1999; Reagans and McEvily 2003; Uzzi and Lancaster 2003). Still others point to their benefits for coordinating action (Obstfeld 2005). Absent information about what actually happens in social network transactions, it is very difficult to adjudicate these conflicting claims.

Work in education has begun to address this issue by developing methods to attend to the content of interaction in social networks. This work demonstrates that teachers' social networks vary considerably in the depth of interaction (Coburn and Russell 2008; Horn and Little 2010), from quick exchanges about how students are doing or a pending deadline to in-depth and substantive conversations about mathematical content or the nature of student learning. Depth of interaction varies even in networks with similar structure or resources (Coburn et al. 2012). Interactions at contrasting depth have different potential to foster the valued outcomes identified by social network theorists, making it more or less likely that individuals share valuable information even if they have it available, engage in joint problem solving, or learn in interaction with others.

In spite of increased interest and attention to sustainability, there is surprisingly little empirical research that employs research designs suitable for investigating the phenomenon. Studies that do highlight the role of teachers' social relations as a key factor in promoting sustainability suffer from methodological limitations. Existing research on social networks is useful because it identifies dimensions of teachers' social relations that may matter for sustainability. But because each line of research tends to focus on a single dimension of networks to the exclusion of others (e.g., tie strength or access to resources), we know little about how these dimensions might interact to influence change in practice. Furthermore, research on social networks both inside and outside of education has focused on either adoption or implementation. Thus, in spite of promising preliminary research in education that points to the importance of teachers' social relations, we know little about how the quality and configuration of teachers' social networks are related to their ability to sustain new instructional approaches over time.

Method

To investigate the relationship between teachers' social networks and sustainability, we draw on data from a longitudinal study that investigated how district reform strategies interacted with human and social capital in the development of teachers' capacities to enact new approaches to the teaching of mathematics.[1] Specifically, we studied teachers in four urban elementary schools in a single southwestern school district across 3 years to investigate the relationship between their social networks and their ability to sustain new instructional strategies after supports for the mathematics initiative were removed.

Context and Sample

Greene School District is a mid-size urban district that was in the first year of its efforts to improve elementary mathematics instruction in the first year of the study.[2] The district sought to improve teachers' instruction by emphasizing a more conceptually-based, student-centered mathematics approach encouraged by the National Council of Teachers of Mathematics (1989, 2000). In order to support teachers' ability to enact this new approach, the district adopted the curriculum *Investigations in Data, Numbers, and Space* in the 2003–4 school year after piloting selected units the year before. *Investigations* embodies a conceptual approach to mathematics learning by focusing on the development of students' understanding of the "big ideas" in elementary mathematics rather than emphasizing the use of correct algorithms and memorization as mathematics curricula traditionally do (TERC 2011). By having students engage in explorations and problem solving, often in real-world contexts, the curriculum provides opportunities for students to learn to think, reason, and make sense of mathematics. This approach is demanding for teachers to implement well because instead of simply demonstrating one correct way to solve each type of mathematics problem, teachers must listen to and interpret student thinking and then subtly steer their thinking toward the canonical mathematical ideas that are the goal of the lesson (Stein et al. 2008). Because many teachers are unaccustomed to teaching in this manner, the curriculum and the pedagogical approaches it promotes typically require high levels of teacher learning to implement well (Stein and Kim 2009). Throughout this article, we refer to this pedagogical approach as "reform-related instructional strategies."

In fall 2003, the district launched an initiative to support this learning. Among other things, they initiated school-based instructional coaches, who were supported by the district and worked with teachers one-on-one and in groups. The district also instituted biweekly school-based professional development in mathematics instruction, periodic district-wide workshops, and weekly grade-level meetings to facilitate joint planning. But, in year 3, after a change in district leadership, the district shifted its priorities and withdrew support for the initiative. Professional development at both the district and school level was redirected to focus on English language learning (ELL) strategies. Budget and staffing decisions were rolled down to the school level, and many principals decided to cut or reduce mathematics coaches. All four schools we studied went from either two or three half-time coaches in years 1 and 2 to a single half-time coach in year 3. Mathematics instruction was cut from 90 to 60 minutes a day to make room for 30 minutes a day of strategies for supporting English language learners. Because virtually all supports for the approach to mathematics embedded in the *Investigations* curriculum were withdrawn in the third year of the study, we had an ideal opportunity to investigate issues of sustainability in real time.

Consistent with the exploratory, theory-building purpose of our study, we used purposive sampling (Strauss and Corbin 1990) to select elementary schools and teachers within those schools for our study. Because the overall study was interested in how schools with contrasting organizational conditions—different levels of social and human capital—implemented the new mathematics curriculum, we sought four schools that varied along these two dimensions. Selection was based on recommendations from the district directors of mathematics. Specifically, we asked the director of mathematics in the district to nominate schools where the faculty had, on average, relatively high and low levels of human and social capital, with human capital described as mathematics instructional expertise and social capital described as interaction about mathematics instruction. The final sample thus included four contrasting organizational conditions: one school with strong professional community and strong teacher expertise, one with strong professional community and weak teacher expertise, one with weak professional community and strong teacher expertise, and one with weak professional community and weak teacher expertise.

We selected four focal teachers in three schools. In the fourth—School H—we were only able to select two focal teachers for logistical reasons. Teachers at all four schools were selected to represent a range of grades and attitudes toward the new curriculum. Two of the original 14 teachers left their schools during the 3 years of the study. Both were new teachers in year 1 and, like many new teachers (Johnson et al. 2005; Loeb and Reininger 2004), decided to leave the profession after a few years of teaching. For this article, we included only the 12 teachers for whom we have 3 years of data (see the methodological appendix [app. D], available online, for more information on sampling, the selected schools, and the 12 focal teachers).

Data Collection

To analyze the relationship between teachers' social networks and sustainability, we relied primarily on interviews, observations, and document analysis. We conducted two interviews and two classroom observations with each focal teacher in year 1. We then expanded our data collection in years 2 and 3, collecting five interviews and six classroom observations for each focal teacher. Each year we also conducted one to two interviews with mathematics coaches, two interviews with the school principal, and one interview with six additional teachers (whom we called nonfocal teachers). We also observed three to five occasions in each school where teachers interacted on matters of mathematics instruction (professional development, grade-level meetings, coaching sessions, etc.).

Social network data.—A subset of this data collection was designed specifically to investigate focal teachers' social networks. We took an egocentric approach to social network analysis. In this approach, the analyst maps networks that are centered around an individual or social unit (the ego; Wellman and Berkowitz 1988). To do this, we interviewed focal teachers individually, using questions designed to find out who a teacher talked with about mathematics instruction (both inside and outside of the school) and the frequency and content of their interaction, as well as why they talked with some people and not others. (See the last section of the methodological appendix in the online version of the article for social network interview questions.) We then analyzed these data and selected an additional six teachers to interview in each school (nonfocal teachers) who were part of focal teachers' social networks. We interviewed nonfocal teachers using the same battery of social network questions, supplemented with questions on their use of curriculum and background in mathematics. This approach allowed us to further investigate the qualities of focal teachers' networks, including the location of expertise and content of interaction. We also used the same battery of social network questions with coaches and principals.

We supplemented the interviews by observing occasions where focal teachers interacted with colleagues identified in their social network interviews and by drawing on select measures from a teacher survey.[3] We used survey questions designed to investigate communication channels to generate our measures for frequency of interaction. Because the survey was not administered in year 1, we used questions from the survey in interviews in year 1 for that information.

Classroom practice data.—To ascertain the degree to which teachers used reform-related instructional approaches, we observed each focal teacher's classroom two times in the spring of 2004 and three times each in the fall and spring of the 2004–5 and 2005–6 school years.[4] Trained observers took ethnographic field notes and then completed a structured analysis upon leaving the classroom. The structured analysis included a lesson summary and answers to questions about cognitive demand, teachers' attention to student thinking, and the location of intellectual authority during the lesson. Each of these dimensions is described below in more depth.

Data Analysis

To analyze how teachers' social networks across the 3 years of the study related to their ability to sustain reform-related mathematics instructional strategies in year 3, we coded multiple dimensions of teachers' social networks and the quality of teachers' reform-related mathematics instruction in each year of the study.

Analysis of social networks.—We mapped each of the 12 focal teachers' networks for each of the 3 years, drawing upon interview data to build egocentric networks. We then analyzed three dimensions of the networks: tie strength, level of expertise, and depth of interaction. To assess *tie strength*, we analyzed the frequency with which a teacher interacted with others in her network. We used questions from interviews in year 1 and surveys in years 2 and 3 that asked: how many times per month do you talk with these individuals about mathematics? Following convention in the literature, we then created an aggregate measure of tie strength across a given network (e.g., Hansen 1999; Reagans and McEvily 2003; Uzzi 1999). Our aggregate measure was the average of the focal teacher's rate of interaction with each individual in her network. We considered a network to have strong ties if teachers reported interacting with others in the network, on average, more than twice a month. (See the methodological appendix online for additional information about social network measures.)

To analyze *level of expertise* in a network, we assessed the degree to which individuals in a teacher's social network had participated in prior professional learning opportunities related to mathematics. (See app. A for definitions of low, medium, and high expertise.) After evaluating the expertise of each individual in a focal teacher's network, we created an aggregate measure of the level of expertise in a given network by calculating the percentage of individuals in a network with moderate or high expertise. To set a cut-point for a high level of expertise, we drew on existing studies of the prevalence of expertise in mathematics among elementary teachers. These studies suggest that expertise in mathematics is rare in elementary schools, with no more than one-third of teachers in a given study having high levels of conceptual understanding (Ball 1990; Ma 1999; Post et al. 1991). Therefore, we considered teachers to have access to high levels of expertise if more than one-third of the individuals in their network had moderate or high expertise.

To analyze *depth of interaction*, we identified 419 instances in our data where the 12 teachers in our sample interacted with others in their social network. We drew on research on teacher interaction (Coburn 2003; Little 1990) to develop criteria for assessing the depth of the content of interaction. Interaction was judged to be at low depth when it focused on surface structures or procedures such as sharing materials, classroom organization, pacing, or how to use the curriculum. Interaction was judged to be at high depth when it addressed underlying pedagogical principles, the nature of the mathematics, or how students learn (see app. A for complete definitions of depth). Because prior studies suggest that high-depth interaction is rare (Little 1982, 1990; Lortie 1975; Sun et al. 2011), we characterized teachers' social networks as high depth if at least one-third of interactions that teachers had with others in their networks was about content judged to be of moderate or high depth (see the methodological appendix online for information about interrater agreement).

Sustainability of reform-related instruction.—We define sustainability as teachers' continued use of reform-related instructional practices in high-quality ways after resources and support for such practices have been withdrawn. This conceptualization is more restrictive than those solely emphasizing endurance of a practice or program over time. We adopt this definition because research suggests that many reforms falter when support for that reform is withdrawn (Coburn 2003; McLaughlin and Mitra 2001) and that for a reform to continue past this point, it must be self-supported and/or institutionalized (see also Johnson et al. [2004] on this point).

Consistent with Bryk and his colleagues (2010) and research on teacher learning (Smith 2000; Stein et al. 2011), we assume that there are multiple pathways to sustainability. Teachers may develop high-quality reform-related practices early in the initiative and maintain them over time. Or they may gradually develop and deepen their enactment over several years such that teachers do not achieve high-quality reform-related instruction until the point when supports for the initiative are withdrawn. Or teachers might develop high-quality reform-related practices early on, decline in the quality of enactment, and regroup and deepen practice in ways that enable them to sustain it over time.

Key to this conceptualization of sustainability is a clear definition of the enactment of reform-related instruction with high quality. We define high-quality reform-related instruction in terms of three hallmarks of a conceptually-based, student-centered approach to teaching and learning mathematics: (1) the ability to set up and maintain high-cognitive-demand instructional tasks, (2) the ability to attend to, elicit, and build upon student thinking in the classroom, and (3) the ability to place the intellectual authority for mathematical correctness on thinking and reasoning rather than the textbook or the teacher. Our conceptualization views the *Investigations* curriculum as a vehicle for guiding teachers toward high-quality instruction, not as an end in itself. As such, our outcome measure is the combination of the above features of high-quality instruction, not fidelity to the curriculum.

To analyze the degree to which teachers taught mathematics using high-quality reform-related instruction, we analyzed the 163 lessons from the 12 focal teachers across 3 years of our study. We drew on the ethnographic field notes from the observation, structured observation analysis, and artifacts from the lesson to code the three dimensions of instruction.

Maintenance of cognitive demand.—Cognitive demand refers to the level of thinking and reasoning that is required for students to successfully complete a mathematical task (Doyle 1983; Stein et al. 1996). However, even if a mathematical task from the curriculum has a high level of demand, teachers may (knowingly or unwittingly) lessen the cognitive demand of the task when they set it up in the classroom (e.g., by inserting easier numbers into the problem or by providing "hints" regarding what to look for) or as students work on the task (e.g., by "taking over" and doing the thinking for the students instead of allowing them to struggle). Lessons that maintain a high level of cognitive demand throughout are associated with greater student learning gains than are lessons in which the level of cognitive demand starts out at a low level or declines during the course of the lesson (Stein et al. 1996; Stein and Lane 1996).

To analyze the degree to which teachers maintained cognitive demands of mathematical tasks, we identified five types of instructional tasks, two with high cognitive demands (doing mathematics and procedures with connections to meaning) and three with low cognitive demands (procedures without connections to meaning, memorization, unsystematic or nonproductive exploration). (See app. B for definitions of the different types of tasks.) Teachers received a "high" rating for cognitive demand if they maintained a high cognitive demand as they moved from the materials to the set-up of the task in the classroom to the enactment of the task in all but one of their lessons in a given year.[5] (See app. C for more detail on coding for reform-related instructional practice.)

Attention to student thinking.—Teachers who enact reform-related instruction with high quality attend to student thinking. That is, they are able to identify the mathematical learning potential of strategies students use to solve mathematical problems and identify which student responses would be important to share with the class as a whole during the ensuing discussion (Brendefur and Frykholm 2000; Lampert 2001; Stein et al. 2008). To assess attention to student thinking, we assigned each lesson a score of 0 to 3 depending on the extent to which teachers uncovered student thinking and made it available to other students to help the class's learning as a whole, with 0 points if the teacher did not try to uncover student thinking and 3 points if the teacher asked students to publicly share their thinking, purposefully selected some student to share their work, and connected or sequenced student responses in meaningful ways. Teachers received a "high" rating for their attention to student thinking across a year if they received a yearlong average above 1 across all lessons.

Intellectual authority.—We analyzed the extent to which the intellectual authority in the classroom was vested in mathematical reasoning rather than the teacher or text. A learning environment embodying the norm of accountability to the discipline regularly encourages students to account for how their ideas make contact with those of other mathematical authorities, both inside and outside the classroom (Cobb et al. 1997; Lampert 1990). Each lesson was assigned a score of from 0 to 2, depending on the extent to which the majority of the students had such opportunities, where 0 meant that judgments of correctness derived from the teacher or the text and 2 meant that judgments of correctness derived from mathematical reasoning. Teachers received a "high" rating for intellectual authority if they received a yearlong average above 1 across all their lessons.

Next, we computed an aggregate rating for instructional quality that combined lessons and dimensions for a given year. We considered a teacher to be enacting reform-related instruction with high quality in a given year if her lessons were above the bar of high quality for cognitive demand and either student thinking or intellectual authority. While previous research has used the maintenance of high cognitive demand as an all-encompassing measure of high-quality reform mathematics instruction (Henningsen and Stein 1997; Stein and Lane 1996), Greene's reform effort also focused strongly on teachers' interaction with students and their ability to support students' use of mathematical strategies. Thus, we reasoned that requiring high attention to student thinking or high reasoning-based intellectual authority—in addition to maintenance of cognitive demand—was a demanding, but realistic, requirement for a rating of high quality.

Finally, we considered a teacher to have sustained reform-related instruction if she or he was able to maintain or develop high-quality reform-related instruction in year 3 after the district withdrew all resources and other supports for this form of instruction. Figure 1 provides a representation of how we

Maintained high cognitive demand in all but 1 lesson in Y 3	+	Intellectual authority average above 1 in Y 3	OR	Student thinking average above 1 in Y 3

FIG. 1.—Sustainability of high-quality reform-related instruction

drew on multiple analyses to assess sustainability of high-quality reform-related instruction.

Qualitative Comparative Analysis

After the social network data and the classroom data were coded, we sought to understand the relationship between the two using a technique called qualitative comparative analysis (QCA). Rather than relying on probability and statistics, as is commonplace in quantitative analysis, QCA draws on set theory and uses Boolean algebra (formalized logic) to investigate complex social phenomenon. The approach is particularly well suited to research that involves a small number of cases and a large number of conditions that may be relevant for the phenomenon of interest (Ragin 1987; Rihoux and Ragin 2009). It is also well suited for exploratory analysis of the sort we pursue in this article, as it enables the researcher to engage in systematic and disciplined comparison across multiple, multidimensional cases, using a structured dialogue between theory and empirical data to surface new relationships that build and extend theory (Rihoux and Ragin 2009).

Rather than having additive or linear assumptions about the impact of various conditions on an outcome, QCA assumes that a given condition may work differently depending on how it interacts with other conditions, forces, or contexts. Thus, it focuses attention on how configurations of conditions—what Ragin calls "causal recipes"—interact with one another in specific settings with consequences for a given outcome (Ragin 2008). QCA is also rooted in an assumption of multiple conjunctural causation. That is, it allows for the possibility that more than one configuration of conditions can lead to the same outcome. The goal of QCA is to identify all of the configurations of conditions that can account for all cases with a given outcome. Thus, the researcher does not try to "specify a single causal model that fits the data best," but instead seeks to "determine the number and character of the different causal [recipes] that exist among comparable cases" (Ragin 1987, 167).

In QCA, the analyst begins by selecting conditions that are theoretically associated with the outcomes of interest. We defined the outcome of interest as high-quality reform-related instruction in year 3. We then drew on our conceptual framework to select conditions that preexisting theory suggested might be associated with this outcome: the presence or absence of high-depth interactions, high level of expertise, and strong ties in all 3 years. Following standard protocol for QCA, we used the software *fs*QCA to array the conditions and outcome in a "truth table" that lists all logically possible combinations of conditions and the empirical outcome associated with each. The truth table enables the analyst to assess the degree to which a given condition or configuration of conditions leads to consistent outcomes (all negative or all positive), a metric known as set-theoretic consistency. If a configuration of conditions is not associated with consistent outcomes across cases, then the conjecture that this set of conditions is associated with that outcome is not supported. Generally, a model—a set of configurations of conditions—is supported if it attains a consistency of .80 or higher (Ragin 2008). The analyst also assesses the degree to which the configurations of conditions that are identified, taken together, can account for all the positive cases (Rihoux and Ragin 2009), a metric known as set-theoretic coverage. Coverage is a measure of the strength of the model. For example, one can attain consistent results but only be able to account for a small percentage of overall cases, indicating that the explanation is not very strong. The goal is to identify a model that can account for all of the cases in the sample, but coverage of at least .80 is considered acceptable.

We defined our outcome of interest as high-quality reform-related instruction in year 3. We then drew on our conceptual framework to select conditions that preexisting theory suggested might be associated with this outcome: the presence or absence of high-depth interaction, high level of expertise, and strong ties in all 3 years. We found that this set of conditions did not yield consistent solutions. That is, there were configurations of conditions that led to both positive and negative outcomes. This suggests that the social network conditions across all 3 years cannot account for teachers' ability to sustain reform-related instruction in year 3.

In QCA, if the configurations of conditions in the truth table do not yield consistent outcomes or if they cannot account for a sufficient portion of cases, the analyst draws on theory or in-depth knowledge of the cases to either add or remove a condition or combination of conditions from the model. The analyst proceeds in step-wise fashion until he or she establishes the combination of conditions that yield consistent outcomes, that makes sense theoretically, and that can account for all of the cases in the sample (Rihoux and Ragin 2009).

We reasoned that a teacher's ability to sustain instruction in the face of challenging conditions may be rooted in the development of strong understanding of pedagogy and student learning (Gersten et al. 2000; Klingner et al. 1999; McLaughlin and Mitra 2001). This understanding may not be developed in the moment but rather over the course of several years, suggesting that the nature and configuration of the social network in year 3 may be less important than in years 1 and 2. We developed a new truth table that included social network dimensions from the first 2 years only. This truth table attained perfect consistency and could account for all positive outcomes. This finding suggests that the three social network conditions in years 1 and 2, taken together, could account for the presence or absence of high-quality reform-related instruction in year 3.

Anonymous reviewers raised questions about whether the quality of teachers' enactment in years 1 and/or 2, teachers' expertise at the start of the study, or school leadership might also play a role in teachers' ability to sustain reform-related instructional practices in year 3. In response, we generated truth tables that added membership in a school (to capture school leadership), high-quality reform-related instruction in year 1, high-quality instruction in year 2, and teacher expertise alone and together to the social network conditions already in the model. The addition of membership in a school and teachers' expertise did not generate set-theoretic consistency at an acceptable level. Therefore, the analysis does not support the conjecture that social network conditions in combination with expertise, membership in a school, or both are associated with high-quality instruction in year 3.

However, adding the presence or absence of high-quality reform-related instruction in year 2 to our previous model did generate configurations of conditions that had high consistency and high coverage. Thus, while a model with social network conditions in year 1 and 2 could account for the presence or absence of high-quality instruction in year 3, adding high-quality instruction in year 2 created an enhanced model that illuminated the configuration of conditions associated with high-quality reform-related instruction in year 3 with more precision.

Finally, we added the quality of reform-related instruction in year 1. This model generated the same set of causal recipes as the quality of instruction for year 2 along with the social network conditions. In other words, including high-quality instruction in year 1 did not add to the explanatory power nor did it modify the influence of the other combined conditions. This suggests that the same configurations of conditions were associated with high-quality instruction in year 3, whether or not a teacher had high-quality instruction in year 1 (Ragin, personal communication, January 2012). For this reason, we proceeded with our analysis with the following conditions in our model: the presence or absence of high-depth interactions, high level of expertise, and strong ties in years 1 and 2, and the presence or absence of high-quality reform-related instruction in year 2.

Given the number of conditions included in the model (seven), there were 128 potential configurations of these conditions that teachers could experience. As is typical, given the combination of the limited diversity in the natural world and the small *n* of our study (Ragin 2008), our focal teachers represented empirical instances of a subset of these possible configurations of conditions: the 12 focal teachers represented 11 of these possible configurations of conditions, described in table 1.

We then used Boolean minimization to simplify the 11 expressions. Key to Boolean minimization is the idea that if cases differ in only one condition but share the same outcome, then the condition that is not shared between the two is irrelevant for producing the outcome and can be removed. The *fs*QCA software moves in step-wise fashion, eliminating a single condition at a time until it identifies the minimum number of combinations that can account for all the positive cases.

Once we identified a small number of configurations of conditions associated with high-quality reform-related instruction in year 3, we turned our attention to understanding configurations of conditions associated with the absence of high-quality instruction. Rather than assuming negative outcomes occur because of the absence of the configuration of conditions associated with positive outcomes (what Ragin terms "the assumption of causal symmetry"), it is important to run QCA analysis to identify necessary and sufficient conditions associated with negative outcomes as well (Rihoux and Ragin 2009; see also Bryk et al. [2010] for a discussion of the importance of testing both positive and negative outcomes). Thus, we ran the analysis with the same set of conditions, but with the outcome "absence of high-quality reform-related instruction in year 3."

Finally, we returned to the data from the cases to understand more about how the conditions identified interacted with one another in each of the identified configurations of conditions and how that related to patterns of instruction in year 3. This last step is crucial. The results of QCA are not the endpoint in the analysis but must be interpreted with the use of theory and data to ensure the interpenetration of theory and data that is at the heart of case-oriented qualitative research (Ragin 1987, 2008).

Findings

When Greene School District withdrew support for teachers' enactment of reform mathematics instruction during the third year of the initiative, many teachers in our study felt unsure about the continued direction for mathematics

TABLE 1

Presence or Absence of Social Network Conditions and Outcome of Interest

CONDITIONS								
Y1 Depth	Y1 Expertise	Y1 Tie Strength	Y2 Depth	Y2 Expertise	Y2 Tie Strength	Y2 High-Quality Instruction	OUTCOME: Y3 HIGH-QUALITY INSTRUCTION	TEACHER
0	1	0	1	1	1	1	1	Xandria, Denise
0	0	0	1	1	1	1	1	Nina
0	0	1	0	1	0	1	0	Sarah
0	1	0	0	0	1	0	0	Tara
0	1	0	1	0	0	1	0	Larissa
0	1	1	0	0	1	1	0	Winona
0	1	1	1	0	0	1	1	Kathy
0	1	1	1	1	0	1	1	Laura
1	0	0	1	0	1	0	0	Don
1	0	1	1	1	1	1	1	Quinn
1	1	1	0	1	0	0	1	Florence

NOTE.—1 = presence of a given condition or outcome; 0 = absence of a given condition or outcome.

in the district. Pressure to focus attention on literacy and instruction for English language learners and a loss of assistance to deepen mathematics instruction contributed to this uncertainty. One teacher in School G explained: "Sometimes you don't get the help. . . . Everybody's complaining, everybody's upset and struggling because they just don't know what to do [with mathematics instruction]." Compounding the challenge, the district changes also had an impact on teachers' social networks (see Coburn et al. [2012] for more details). Nearly all focal teachers' networks had weaker ties, provided less access to expertise, and had fewer high-depth interactions in year 3. Yet, in spite of this loss of support from the district and teachers' social networks, more than half of the teachers in our sample were able to sustain high-quality reform-related instruction in year 3. Why were some teachers able to sustain reform-related instructional practice in the face of such challenging circumstances and others were not?

We found that the configuration of teachers' social network conditions in the first 2 years contributed to or hindered teachers' ability to sustain reform-related instructional approaches in high-quality ways. We identified three configurations of conditions that were associated with high-quality instruction in year 3 (see table 2). All three involved a combination of high depth, high expertise, and strong ties. Two configurations of these conditions involved the simultaneous presence of all three in a single year, and one involved strong ties and high expertise in year 1 followed by high depth in year 2.

We also investigated the configuration of conditions associated with the inability to sustain high-quality instruction in year 3. Table 2 shows that the absence of strong ties in year 1 and the absence of high level of expertise in year 2 or the absence of high-depth interactions in both years was associated with the lack of high-quality reform-related instruction in year 3.

In the section that follows, we illustrate how these various configurations of conditions were related to teachers' ability to sustain reform-related instruction in year 3. We argue that social networks fostered teachers' ability to enact high-quality reform-related instruction in year 3 when they provided supports necessary for teachers to develop strong understanding and deep enactment of new instructional strategies. This strong understanding helped teachers maintain reform-related strategies in the face of reduced supports and changing conditions in year 3. In the section below, we illustrate these claims by profiling each configuration of conditions.

Synergy: High Depth, High Expertise, and Strong Ties in the Same Year

Most teachers who were able to sustain or improve reform-related instruction in year 3 had 1 year when their social network simultaneously had a high

TABLE 2

Configurations of Social Network Conditions Associated with High-Quality Instruction in Year 3

	Consistency	Coverage	Teachers
Configurations associated with year 3 high-quality instruction:			
1. (Y2 DEPTH * Y2 EXPERTISE * Y2 TIE STRENGTH) * Y2 HIGH-QUALITY INSTRUCTION	1.0	.57	Quinn, Xandria, Nina, Denise
2. (Y1 DEPTH * Y1 EXPERTISE * Y1 TIE STRENGTH) * (Y2 EXPERTISE * yr2 tie strength)	1.0	.14	Florence
3. (Y1 expertise * Y1 TIE STRENGTH) * (Y2 DEPTH * y2 tie strength) * Y2 HIGH-QUALITY INSTRUCTION	1.0	.29	Kathy, Laura
Total	1.0	1.0	
Configurations associated with year 3 absence of high-quality instruction:			
4. y1 tie strength * y2 expertise	1.0	.6	Tara, Don, Larissa
5. y1 depth * y2 depth	1.0	.6	Tara, Sarah, Winona
Total	1.0	1.0	

NOTE.—It is the convention in Boolean algebra to represent the presence of a condition with capital letters and the absence of a condition with lower case letters; * represents the logical AND. As is the convention in qualitative comparative analysis, the expressions above represent the intermediate solution, which uses conservative assumptions in the simplification process.

level of expertise, a high percentage of moderate- and high-depth interaction, and strong ties. Quinn, Xandria, Nina, and Denise had all three social network conditions in year 2 (configuration 1); Florence had them in year 1 (configuration 2). Having all three social network conditions at the same time seemed to create a synergy that fostered exceptional learning conditions, contributing to teachers' ability to sustain the reform in year 3.

Social networks with all three social network conditions in a single year created multiple opportunities for teachers to learn about the new instructional strategies. For example, Quinn, a fourth-grade teacher in School H, had all three social network conditions in year 2. That year Quinn's social network included her fourth-grade colleagues, two coaches, and several administrators. A relatively high proportion (44%) of the people in her network had moderate or high expertise. Quinn interacted with others in her network frequently—an average of 2.5 times per month—an indicator of strong ties. And when she did so she was likely to discuss substantive issues of mathematics teaching and learning: 84% of her interactions were at moderate or high depth.

This configuration of network conditions was potent. Because Quinn's interactions were likely to be at moderate or high depth, she was able to work on issues that were at the core of the instructional approaches she was trying to enact. For example, most of her interactions with colleagues in year 2 focused on how to ask students questions to elicit their strategies for problem solving and then draw on and leverage student strategies during class discussions to foster student learning. Because there was a high percentage of people with expertise in her network, when interaction focused on these substantive issues, expert others were able to infuse the conversation with knowledge that Quinn did not herself possess. In one observation, fourth-grade teachers were discussing student responses on an open-ended assessment. Some in the group, including Quinn, were confused about the difference between factors and multiples. The coach, who had a moderate level of expertise, clarified the distinction and facilitated a discussion of instructional strategies to teach the relationship between these concepts. Quinn had the additional support of strong ties with her network: because she met with others frequently, she was able to discuss an issue, experiment with it in her classroom, and bring it back to her colleagues for further conversation, thus strengthening her understanding of the new instructional approaches.

While Quinn had made considerable strides in her use of the new instructional approaches in year 1, the combination of high depth, strong ties, and high expertise in year 2 appeared to enable her to strengthen her enactment of reform-related strategies. For example, while Quinn failed to maintain the cognitive demand of any tasks we observed in year 1, she was able to maintain high cognitive demand in all but one in year 2. Her instruction in year 2 was also characterized by keen attention to student thinking and a growing attention to intellectual authority. Thus, she not only met but exceeded our definition of high-quality instruction. For example, in one lesson during year 2, Quinn provided the following problem to her students: “A pet store has 75 fish. A new shipment arrived. Now the store has 200 fish. How many fish did the store receive in the shipment?” Quinn had several students share their strategies for solving the problem, facilitating a discussion where the class compared strategies. Quinn elicited student thinking and strategically linked students’ problem-solving strategies together to assist them in moving toward an understanding of different multiples of 5 and 25, a key goal of the lesson. Others took notice of Quinn’s improvement in year 2. The coach remarked: “Quinn’s really grown. When she first started here, she was very much a traditional teacher. ‘Do what I say, when I say.’ . . . She has really grown to getting kids to do the talking.”

Solid enactment of reform-related instruction seemed to enable Quinn to sustain her reform-related instruction in year 3 when the district withdrew support for this approach. Despite limited interaction in her social network in year 3, limited interaction with the remaining mathematics coach, and having to contract her lessons from 90 minutes into a 60-minute time frame, Quinn was flexible enough with her enactment that she made adjustments to the *Investigations* lessons in ways that continued to maintain quality instruction.

Importantly, the presence of all three social network conditions along with high-quality enactment in year 2 was sufficient to support sustainability in year 3 regardless of teachers’ level of enactment prior to the study. Three out of four teachers who had this configuration of conditions had no experience with this approach to mathematics teaching prior to year 1. Furthermore, two teachers—Xandria and Deanna—continued to have low-quality enactment at the end of year 1. Yet, these teachers were nonetheless able to leverage social networks with high depth, high expertise, and strong ties in year 2 to develop high-quality reform-related instruction by the end of year 2 and sustain it in year 3.

Finally, having all three network conditions concurrently in year 1 worked somewhat differently than having them in year 2; the QCA suggests that three conditions in year 1 alone were not sufficient to support sustainability without also having strong expertise and weak ties in year 2. Although all three network conditions in year 1 seemed to create a synergy of learning opportunities that enabled teachers to develop strong enactment, perhaps because it was the first year and the approach was still so new, teachers needed the occasional support of an expert network in year 2 to maintain high-quality enactment into year 3. For example, Florence, an experienced kindergarten teacher in School G, had all three social network conditions in year 1 with a network that stretched beyond her grade-level colleagues to include two coaches and members of a district-level mathematics task force. Florence was able to leverage her frequent, high-depth interaction with expert others to help her develop high-quality instruction that year. In year 2, Florence did not feel that she needed the strong ties that frequent interaction brings. She reported: “Because we are pretty familiar with what’s to come next, there’s probably less discussion than there was. . . . I think [I’m] being pretty self-sufficient with it.” She did continue to reach out to others in her network, 43% of whom had expertise, in year 2, but, she did so infrequently, an average of just over one time a month. At the same time, she did need the access to expertise to maintain high-quality instruction. Initially, Florence’s enactment declined in year 2, mainly because she selected only low-level tasks from the kindergarten curricula during observations in the fall. But, as she engaged with more expert others across the year, they encouraged her to select higher-level tasks such that by the end of the year, she was enacting high-level tasks with high quality. She was subsequently able to sustain high-quality, reform-related instruction in year 3 in spite of the fact that she had almost no interaction with others about mathematics in that year. In sum, Florence, like Quinn and others, drew on the synergistic combination of strong ties and high-depth interaction with a relatively expert network in a single year to develop the strong understanding and enactment of the reform mathematics approach necessary to make principled adjustments that sustained high-quality instruction in the face of changing and challenging conditions in year 3.

Adding Depth over Time: High Expertise and Strong Ties in Year 1 Followed by High Depth in Year 2

Teachers were also able to sustain high-quality reform-related instruction in year 3 when they had networks characterized by high expertise and strong ties in year 1 followed by networks characterized by high-depth conversation in year 2 (configuration 3). Two teachers had this configuration of social network conditions: Kathy and Laura.

Social networks with the combination of strong ties and expertise in year 1 enabled Kathy and Laura to develop a basic understanding of reform mathematics strategies. Second-grade teacher Kathy had strong ties (interacting an average of 3.3 times per month per person) with three grade-level peers and two coaches. But, despite a high level of expertise in her network, Kathy’s discussions tended to focus on basic features of the reform mathematics approach: discussions about logistical issues, materials, and pacing. Drawing on frequent low-depth interactions with expert colleagues, Kathy was able to use reform-related instructional strategies consistently but was not able to enact them with high quality in year 1.

In year 2, targeted, high-depth interactions enabled Kathy to build on the foundation she laid in year 1 to achieve high-quality instruction by the end of the year. Kathy had weaker ties with colleagues in her year 2 network, interacting an average of 1.63 times per month (compared to 3.3 times per month in year 1). However, when Kathy did interact with others, she tended to do so with greater depth. Sixty-four percent of Kathy's year 2 interactions were at moderate or high depth and targeted core features of the reform mathematics approach. For example, she discussed how to use well-crafted questions to uncover students' conceptual understanding with her colleagues. She also observed her coach questioning students about their problem-solving strategies in a mathematics lab and then talked with the coach and other colleagues about the ways the coach orchestrated the student discussion.

The targeted high-depth interaction in year 2 enabled Kathy and Laura to achieve high-quality enactment that year. In Kathy's case, high-depth interaction focused on how to question students to support their mathematical understanding. These same ideas manifested in her instruction, specifically her use of mathematical reasoning to judge the correctness of students' solutions by asking students targeted questions. In one lesson, students worked in groups to find different combinations of coins to make a given amount of money. Kathy moved to each group asking students questions about their strategies for solving the task. When students explained their solutions, rather than simply verifying the accuracy of solutions Kathy prompted them to justify their answers using counting. That is, she located intellectual authority in mathematical reasoning, a key tenet of high-quality instruction.

Weak ties in year 2 were also a condition in Kathy and Laura's configuration of social network conditions, suggesting that high-depth interactions coupled with high-quality enactment of reform strategies supplanted the need for frequent interaction. Both teachers interacted substantially less often in year 2 than year 1. Having built a basic understanding in year 1, substantive interactions targeting reform mathematics strategies were perhaps more important than frequent interactions in year 2. Furthermore, this configuration of social network conditions was sufficient regardless of whether teachers achieved high-quality enactment of reform-related strategies in year 1. Kathy did; Laura did not.

Strong ties and expertise in year 1 followed by high-depth interaction in year 2 enabled Kathy and Laura to sustain high-quality reform-related instruction in year 3. This is especially noteworthy since both teachers switched to new grade levels in year 3, requiring them to learn all new instructional materials just as network supports largely ended. Having developed sufficient understanding of reform instruction, both teachers were able to apply the approach with flexibility to a new grade level. For example, Kathy achieved sustainability in year 3 by continuing to enact instructional strategies acquired through network interactions in the first 2 years: in particular, she continued to progress in her ability to employ mathematical reasoning when examining student solutions.

Not all teachers had configurations of network conditions that provided sufficient support to develop high-quality instruction in the first place, let alone sustain it in year 3. Here, we describe two configurations of conditions associated with the absence of high-quality, reform-related instruction in year 3.

Missing Pieces: Absence of Strong Ties in Year 1 and Absence of Expertise in Year 2

Three teachers had a social network characterized by an absence of strong ties in year 1 and an absence of expertise in year 2 (configuration 4): Larissa, Tara, and Don. While teachers in this configuration did some good work, they were missing important network conditions to develop a strong understanding and enactment of reform-related instruction.

An absence of strong ties made it difficult for teachers with this configuration of conditions to lay the groundwork for strong enactment in year 1. In contrast with Kathy and Laura, whose combination of strong ties and expertise in year 1 enabled them to make considerable progress, Larissa, Tara, and Don did not interact frequently enough to make use of the expertise or depth that they had in their network. By the end of year 1, they still had not put even the basic elements of high-quality reform-related instruction in place. For example, Don, a fifth-grade teacher in School F, had a network with high-depth interaction but weak ties. He did have substantive interactions with his colleagues, many of which focused on strategies for eliciting student thinking. However, perhaps because he was not able to revisit this difficult-to-learn instructional approach in more frequent communication with colleagues, Don was not able to integrate this approach into his classroom instruction. By following the teacher script in the curriculum quite closely, he was able to maintain the cognitive demands of tasks in year 1, but he tended to give students the answer rather than use approaches to draw out student thinking. Thus Don, like the other teachers with this configuration, had enactments of reform-related strategies that were either low quality or just on the cusp of high quality but fragile.

In year 2, the absence of expertise in their networks meant that teachers with this configuration of conditions had difficulty further improving their practice to achieve consistent, high-quality instruction. For example, Larissa, a third-grade teacher in School G, had stronger enactment going into year 2 than Don. However, the limited expertise in her network in year 2 was problematic for Larissa, who struggled with knowing what to do after she had used the new instructional strategies she was learning to elicit student thinking. In an interview after a lesson where students used straws of different lengths to make triangles, Larissa pointed to a moment in the lesson when a student came up with a surprising strategy for combining the straws, remarking that she had no idea how to respond to the student. Instead of using this student's novel solution strategy to help extend students' understandings of the relationship between angles in triangles, Larissa cut the conversation short, missing a key opportunity to enact a strong lesson in support of student learning. Absent access to expertise to strengthen their understanding and enactment of reform strategies in year 2, Larissa and Don's instruction remained stable. For Don, this meant that his instruction remained inconsistent but ultimately was of low quality. For Larissa, who had made considerable strides in year 1, this meant that her instruction remained just on the cusp of high quality.

Lacking strong enactments of reform-related strategies, the teachers with this configuration were unable to sustain or improve their instruction in year 3 in the face of changing and difficult conditions. For example, even though Larissa had achieved high-quality reform-related instruction in year 2, she lacked the understanding and flexibility to make principled mathematically and instructionally sound adaptations to the new conditions. Faced with the need to reduce mathematics instruction from 90 to 60 minutes and adjust to a class of children that she felt were less prepared than in previous years, Larissa made a series of modifications to the curriculum that lowered the cognitive demands of tasks from the outset. Then, when students encountered difficulties, she tended to respond by telling students the answer, short-circuiting their engagement with mathematical reasoning and lowering the cognitive demands of the task. While she maintained the cognitive demands of all but one task in the first 2 years, she lowered the cognitive demands in every task except one in year 3.

Although all teachers in the sample faced the kind of challenges Larissa and Don faced in year 3 (and some teachers, like Kathy and Laura, faced the arguably greater challenge of learning a new grade-level curriculum), Larissa and Don were not well prepared to handle these challenges. Absent the solid understanding of the reform mathematics approach that Quinn, Kathy, and others developed in the first 2 years, Larissa and Don made choices that resulted in a substantial decline in the quality of their instruction in year 3.

Scratching the Surface: Absence of Depth in Years 1 and 2

Finally, the three teachers who lacked depth in both year 1 and year 2 (configuration 5)—Tara, Sarah, and Winona—were also unable to develop or sustain high-quality reform-related strategies in year 3. These teachers engaged in few conversations with others about substantive issues related to reform instruction in either year. As a consequence, they either never managed to enact the reform mathematics approach with high quality or lacked the understanding and enactment necessary to sustain that approach in year 3 when the initiative was curtailed.

Teachers with this configuration of social network conditions had network interactions characterized by brief, superficial conversations in years 1 and 2. For example, Tara, a fourth-grade teacher in School G, characterized the nature of her interaction with the coach in the following way: "I like to go share with [the coach], 'Hey, you know this worked out,' 'cause a lot of times it'll be something that I don't think they'll get, and I'll be really nervous about it. And, sure enough, they did get it." Similarly, Sarah, a first-grade teacher in School E, described her interaction with her grade-level colleagues in year 2: "I will ask Ms. Moon or the other teachers in our group and they will say 'Well I did it this way and I found that,' and it's just like, 'Oh you did that? That was really good.' That's really kind of how it works."

Lacking more in-depth interaction about the reform mathematics approach, Tara, Sarah, and Winona all had problems maintaining the cognitive demands of tasks that required students to solve open-ended problems where the teacher was expected to support students' thinking. For example, Tara spoke about her struggles to enact a facilitative teaching approach, saying: "My tendency is to want to push them towards that [right answer], and . . . you can't always do that." Tara did choose rigorous, open-ended tasks for her lessons but then inevitably gave students procedures and algorithms to follow rather than asking them questions about their problem-solving work and what they might do next. As a result, Tara's lessons were low quality in both years 1 and 2. When she switched grade levels in year 3 and had even less district support to enact a reform-oriented approach, Tara continued to deliver instruction at a low level.

Unlike Tara, Sarah and Winona enacted lessons with high quality in year 2, but their understanding of the reform mathematics approach appeared to be too fragile to sustain in year 3. Winona's experience is particularly striking, as she had the same social network configuration as Kathy and Laura in year 1: strong ties with high-expertise others. However, unlike Kathy and Laura, Winona lacked the high-depth conversations in year 2 that enabled Kathy and Laura to strengthen their understanding of the reform mathematics approach. Winona's interactions in year 2 were mostly about "problems" and "activities." She specifically noted, "Sometimes we end up talking a lot about management of free choice time and assessment during free choice time." However, she had few deeper discussions about students' mathematical work.

By year 3, when Winona and Sarah had even less interaction with others in their social networks, both teachers delivered lessons that echoed the worst of their instruction in years 1 and 2. Absent sufficient support in those first 2 years to develop facility in probing student thinking and helping students articulate their mathematical reasoning, the teachers did not sustain the high cognitive demand of most mathematical tasks in their year 3 lessons.

Taken together, our analyses highlight several different profiles for social networks that can support or forestall teachers' sustained enactment of reform-oriented mathematics instruction. Teachers with networks characterized by strong ties, expertise, and high-depth interaction (in 1 year or stretched across 2 years) were able to sustain high-quality instruction despite challenging conditions and few network supports in year 3. Teachers missing critical pieces of network support either never achieved or were not able to sustain high-quality instruction when support for these approaches was removed.

Discussion

Schools and classrooms are constantly changing. Teachers face a new group of students each year with different strengths and needs. Teachers change grade levels, requiring them to learn all new materials and adjust their instructional strategies. And, as vividly illustrated by the case of Greene, school and district policy contexts change as well; new priorities, new policy initiatives, and shifting availability of resources create changing conditions in schools and classrooms. The bottom line is that schools never stand still. Thus, sustaining new instructional approaches is not simply about continuing to do the same thing. It requires that teachers and others make continual adjustments to new conditions and needs at the same time that they maintain the underlying pedagogical approach. We provide evidence that teachers with a solid grasp of reform-related instructional strategies are able make adjustments that maintain high-quality instruction.

Teachers' social networks are one way to develop this capacity. In this study, social networks in year 3 were not sufficient to support teachers in sustaining high-quality reform-related instruction that year, perhaps because most teachers' networks in year 3 were characterized by weak ties and low depth. Instead, the quality and configuration of teachers' social networks in the first 2 years assisted teachers to develop a strong enough enactment to sustain reform-related instruction in year 3.

Furthermore, we provide evidence that no single dimension of social networks is sufficient to support sustainability. Teachers with social networks characterized by strong ties, high levels of expertise, or depth alone in a given year may be unable to develop high-quality instruction in the first place or to develop instructional approaches with enough flexibility to adjust to changing conditions. Strong ties only go so far toward supporting implementation if teachers only talk with others about superficial or logistical issues or if the people they seek out lack expertise in reform mathematics. Similarly, having a network with a large percentage of experts may not be sufficient if teachers interact only occasionally with expert others or focus their conversation on logistical or informational matters.

We show that the combination of expertise and tie strength, along with high-depth interaction either concurrently or in the subsequent year, can support the development of strong enactments of reform-related instruction that enables teachers to sustain over time. Having all three social network conditions in a single year may create a great deal of synergy as teachers are able to discuss matters at the heart of the instructional approach with others with expertise with enough frequency that they can experiment with new instructional approaches, discuss them with colleagues, and push their practice further. In this study, teachers who experienced all three social network conditions concurrently in either year 1 or year 2 were able to achieve high-quality instruction that year; however, all three network conditions in year 1 were not sufficient to support sustainability unless teachers also had access to expertise and weak ties in year 2.[6] Teachers were also able to sustain reform-related practices in year 3 when they had high expertise and strong ties in year 1 followed by depth of interaction in year 2. Strong ties and high expertise in year 1 enabled teachers to lay a foundation, which they then were able to deepen the following year via targeted high-depth interaction.

When teachers developed a strong enactment of the new mathematics instructional strategies with support from their networks, they appeared to be able to adjust their practice in ways that maintained high quality when faced with changing conditions and limited support in year 3. Those teachers who lacked these social network conditions in the first 2 years were unable to make such adjustment. The quality of their instruction declined in year 3, and they were unable to sustain the reform.

Limitations

This study is not without limitations. First, we measured tie strength by focusing on frequency of interaction. While many scholars use frequency as a measure of tie strength (Rivera et al. 2010; Uzzi 1996, 1997, 1999), it is important to acknowledge that it is a proxy measure since it does not capture the affective dimension of the relation. Importantly, however, frequency does predict affective dimensions of social relations such as trust and social closeness (Coburn and Russell 2008; Rivera et al. 2010). Frequency and closeness are often highly correlated, suggesting that they are measuring the same underlying construct (Hansen 1999). And, like other ways of measuring tie strength, frequency has been shown to predict outcomes such as altruism, joint problem solving, and information sharing (DiMaggio and Louch 1998; Uzzi 1996, 1997, 1999).

However, given that frequency is not a direct measure of the underlying construct, readers should view our findings related to tie strength with caution.

Second, following convention in the literature, we relied on a summary measure of each dimension of the teachers' social network that we were interested in by averaging across all of an individual teacher's ties. For example, to create our measure of expertise, we calculated the percentage of those in a teacher's social network with moderate or high expertise. There are strengths and limitations of using aggregate measures of social network dimensions in this way. Using aggregate measures creates a summary measure of the network as a whole, providing a concise way to compare different dimensions of a given focal teacher's networks or compare a given dimension across networks. However, any summary measure necessarily simplifies complexity and masks nuance. In this case, the aggregate measures mask the ways that an individual might, for example, have strong ties with some in their networks and weak ties with others. It also masks the interaction between dimensions of the social network at the tie level. For example, do strong ties with individuals with low expertise work differently than strong ties with individuals with high expertise? By using aggregate measures, our analysis provides a necessary first look at how dimensions of social networks interact. Future research can extend this analysis by investigating these interactions at the tie level rather than the network level.

Third, we took an egocentric approach to social network analysis. The strength of the egocentric approach is that we did not make assumptions about the configuration of teachers' social networks but rather took identification of the networks as a first step for investigation. Because the analyst maps networks from the ground up using nominations solicited from the interviewees, the egocentric approach does not assume the locus of professional community is in formal structures such as grade-level groups or even exists within preexisting boundaries such as the school (Carrasco et al. 2006; Reagans and McEvily 2003). In fact, all teachers except for one had networks that spanned beyond the boundaries of their school, which we were able to capture using the egocentric approach. One potential limitation of the egocentric approach is that the researcher typically does not have access to the alters whom the ego nominates, and thus there is limited opportunity to validate the existence of a tie. However, in this study, we addressed this limitation to some degree by administrating social network protocols to nonfocal teachers in focal teachers' networks, who provided further information about the nature of the tie, the expertise at the node, and the content of interaction between the alter and the ego. Another potential limitation of the egocentric approach is that, because we did not do social network analysis with all teachers in the school (as one would with sociocentric approaches to network analysis), we are not able to map network structure for the entire school. As a result, we are unable to analyze dimensions of the structure of networks as centrality or the structure of cliques or subgroups. Future research that uses sociocentric approaches to network analysis is necessary to shed light on the relationship between these additional dimensions of social networks and sustainability of instructional reform.

Implications for Research on Sustainability

In spite of these limitations, this study contributes to research on sustainability by extending our understanding of when and under what conditions teachers' social relations contribute to teachers' ability to sustain ambitious instructional reform. Prior research on sustainability has highlighted the role of teachers' social relations in reform sustainability (Bryk et al. 2010; Datnow et al. 2002; Hargreaves and Goodson 2006; Klingner et al 1999; McLaughlin and Mitra 2001). We extend this research by identifying the specific configuration of social network conditions that seem to matter for sustainability.

Most studies of teachers' social relations have tended to investigate a single dimension of teachers' social relations at a time (e.g., Frank et al. 2004) or to create a scale that integrates multiple dimensions into a single construct (e.g., Bryk et al. 2010; Louis and Kruse 1998), making it impossible to know which dimension or combination of dimensions is actually making the difference. By contrast, we measure multiple dimensions of teachers' social networks individually and use QCA to analyze how different combinations in different years interact to support sustainability. In so doing, we show that no single dimension of social networks appears to be sufficient to support sustainability. Rather, it is the interaction between tie strength, expertise, and depth of interaction that seems to matter for sustainability. Depth of interaction enables teachers to move beyond information exchange or logistical issues to investigate substantive issues that are central to a teacher's ability to learn a new instructional approach. Interaction with expert others brings insight and knowledge to bear on these issues, extending teachers' grasp of the mathematics and new and novel instructional approaches. And, strong ties enable teachers to work iteratively with colleagues to refine their instructional strategies and deepen their enactment over time. We also show that these three network dimensions could be present in at least three configurations: in the first year of the initiative if supplemented with access to expertise in the second year, in the second year of the initiative, or stretched across 2 years with expertise and tie strength in year 1 and depth and weak ties in year 2. By identifying key qualities of teachers' social networks that support sustainability and elucidating the ways in which these qualities interact, we begin to uncover when and under what conditions teachers' social relations serves to support sustainability and when they do not.

This study also provides insight into the possible influence of the length of time that teachers experience these network conditions. In this study, when the district eliminated the structures and activities that it put in place to support teachers' learning, the nature and configuration of teachers' social networks shifted as well (for further discussion on the factors that affected the nature of social networks, see Coburn et al. [2012]). Only two out of the 12 teachers had social networks that were high in more than one dimension in year 3, and most were low in all three. Yet teachers were not only able to develop high-quality enactment of a difficult-to-learn curriculum, they were able to sustain that enactment with 1 or 2 years of favorable network conditions. This suggests that teachers may not need powerful networks for extended periods of time to support sustainability as long as their networks contain a combination of all three network conditions.

It is important to note that this study investigates the relationship between social networks and sustainability of instructional reform in the context of a mathematics initiative that promoted ambitious approaches to mathematics reform. The instructional strategies promoted by the district initiative and the *Investigations* curriculum were challenging for teachers to learn and implement (Stein and Kim 2009). They also departed from teachers' prior approaches to mathematics instruction, at times substantially. This raises these questions: Do teachers need a similar set of social network conditions to support sustainability if the instructional reform is less challenging to learn and enact? Or if it departs less substantially from teachers' existing practice? Is depth of interaction as important if an instructional reform requires less learning on the part of teachers? How about expertise? This study extends research on sustainability by identifying key dimensions of social networks and several patterns of interaction over time that support sustainability of ambitious instructional reform. Future research could build on this work by investigating the relationship between these dimensions of social networks and sustainability for reforms that place different kinds and levels of learning demands for teachers.

Implications for Research on Social Networks

This study contributes to research on social networks by extending it to the issue of sustainability. To date, an extensive body of research investigates the relationship between social networks and diffusion of innovation (e.g., Davis 1991; Valente 1995). This research focuses mainly on the adoption of reform. Yet we know that it is much easier to adopt an innovation than to implement it well (Spillane and Jennings 1997; Spillane and Zeuli 1999). A smaller body of research investigates the relationship between social networks and implementation, studying how features of social networks—most often tie strength, but in educational settings, expertise—influence how people use new approaches in their day-to-day work (Frank et al. 2004; Hansen 1999; Obstfeld 2005; Penuel et al. 2009, 2010; Reagans and McEvily 2003). However, few have studied social networks and implementation over time, and no one has investigated what happens once initial energy, resources, and conditions dissipate. Given how few innovations are actually sustained over time (Cuban 1988), it is important to understand not only how social networks support adoption and implementation but how they foster sustainability as well.

This study also contributes to research on social networks by investigating the nature of social network transactions directly. Few studies investigate what actually happens in social network interactions (Borgatti and Foster 2003; Kilduff and Brass 2010). Instead, they draw inferences about the process from the structure of the network (e.g., nature of ties or the configuration of the network as a whole) or resources available at network nodes (e.g., expertise). But prior research has shown that the content of interaction varies even in networks with similar structure or resources (Coburn et al. 2012). We build on this work to provide evidence that the content of interaction—measured here in terms of depth of interaction—may play a crucial role in teachers' ability to implement and sustain complex instructional approaches. Thus, we uncover a new dimension of social networks that may have important consequences for the degree to which social networks promote a range of valued outcomes, including implementation and sustainability.

Gaining insight into the content of social network transactions is also important because it helps uncover the mechanism by which social networks support these outcomes. There are currently multiple theories in this regard. For example, in the case of tie strength, researchers argue that weak ties with multiple people provide social reinforcement for adoption of new practices (Centola 2010). This argument locates the power of social networks in dynamics of peer pressure and social control (see Frank et al. [2010] for a similar argument regarding expertise). Others argue that strong ties enable the transfer of complex or tacit information (Hansen 1999; Reagans and McEvily 2003) or joint problem solving (Uzzi and Lancaster 2003). In this account, social networks provide their benefits by creating conditions for individuals and groups to learn from and with one another. Finally, still others argue that strong ties facilitate increased coordination and communication (Obstfeld 2005), emphasizing the way social networks facilitate collective action.

While our study cannot resolve the debate about the underlying mechanism, by measuring social network interaction directly we provide support for the learning explanation. We show that when teachers have more substantive, more focused, more targeted talk where they grapple with teaching problems, puzzle over the meaning of mathematical concepts, and brainstorm ways to link instructional strategies to children's current thinking, they are able to move toward deeper enactment and a greater ability to sustain reform. This suggests that the mechanism involved is one of learning rather than social pressure or collective action. If it were social pressure, simply having other people in one's network actively implementing would pressure teachers to make change in practice. But all the teachers in our study had others in their network who were using curricular materials to some degree. And nearly all teachers in our study were themselves trying to make the change. In this study, social networks appeared to foster sustainability when they provided substantive support to help teachers figure out how to make those changes, in the form of talk and expertise and the frequent interaction that gave them access to both of these things. Thus, attention to the content of interaction begins to provide a way to open up the black box of social network transactions, something that is crucial if we are to truly understand how social networks actually promote such well-documented outcomes as joint problem solving, diffusion of innovation, implementation and, now, sustainability as well.

Appendix A

TABLE A1

Definitions of Codes for Dimensions of Social Networks

Code	Definition
Expertise:	
High	High expertise is defined as (1) four or more intensive professional development experiences or (2) a math major in undergraduate or specialization in mathematics education in graduate work accompanied by two or more intensive professional development experiences accompanied by at least some opportunity to learn about pedagogical approaches consistent with the *Investigations* curriculum.
Moderate	Moderate expertise is defined as (1) two or three intensive professional development experiences or (2) mathematics major as an undergraduate or specialization in mathematics in graduate school accompanied by at least some opportunity to learn about pedagogical approaches consistent with the *Investigations* curriculum.
Low	Low expertise is defined as (1) one or fewer intensive professional development experiences and (2) no formal mathematics training in undergraduate or graduate school, or a mathematics major or specialization in mathematics absent at least some opportunity to learn about pedagogical approaches consistent with the *Investigations* curriculum.
Depth:	
Low	Talk related to one or more of the following: how to use materials; how to coordinate between the text, standards, assessments, and pacing guides; how to organize the classroom; sharing materials or activities; general discussions of how a lesson went or whether or not students were "getting it."

Medium	Talk related to one or more of the following: specific discussions of how lessons went that includes a discussion of why; planning for specific lessons that is detailed and includes a discussion of why; specific and detailed discussion of whether students were learning (but not how students learn); discussion of instructional strategies in the context of observations; doing mathematics problems together with discussion.
High	Talk related to one or more of the following: pedagogical principles underlying instructional approaches; how students learn or the nature of students' mathematical thinking; mathematical principles or concepts.

Appendix B

TABLE B1

Types of Instructional Tasks

Type of Task	Description
High level tasks:	
Doing mathematics (DM)	Open-ended problems with limited guidance for students on how to solve them, thus requiring complex, nonroutine thinking and reasoning such as making and testing conjectures, framing problems, representing relationships and looking for patterns
Procedures with connections to meaning (PWC)	Tasks designed to illuminate concepts, meaning or understanding by focusing students' attention on the use of procedures for the purpose of deepening students' understanding of mathematical ideas
Low-level tasks:	
Procedures without connections to meaning (PWOC)	Tasks that focus students' attentions on algorithms and routine procedures without any attempt to foster conceptual understanding
Memorization (M)	Tasks designed to facilitate memorization without any attempt to foster conceptual understanding
Unsystematic or nonproductive exploration (UNE)	Tasks that, as enacted, devolve into exploration that is neither systematic nor productive in developing students' mathematical reasoning or understanding
Unrated tasks: no mathematical activity (NMA)	Tasks that contain no work related to mathematics, including tasks designed to set up later mathematical activities by eliciting information/interest from students and/or providing background information.

Appendix C

TABLE C1

Definitions of Codes for Reform-Related Instructional Practices

Dimension/Score	Definition
Maintenance of cognitive demands:	
Low	In more than one lesson throughout the year, the teacher transformed the lesson's major mathematical task to a low level of cognitive demand either from materials to set up or from set up to enactment.
High	The teacher transformed the lesson's major mathematical task to a low level of cognitive demand either from materials to set up or set up to enactment in *only one lesson or no lessons throughout the year*. For the remaining lessons, the teacher either: (1) Maintained the same high level of cognitive demand from materials to set up and set up to enactment without transforming a task into another type of high-level demand or to a lower level of cognitive demand; *or* (2) Transformed the task from "doing mathematics to procedures with connections" or from "procedures with connections to doing mathematics" from materials to set up or from set up to enactment.
Attention to student thinking and intellectual authority:	
Low	In more than one lesson throughout the year, the teacher received a "0" rating for "attention to student thinking"—meaning the teacher did no work to uncover student thinking—and a "0" rating for "intellectual authority"—meaning the teacher made judgments about correctness based on the teacher or the text only rather than students' mathematical reasoning in the classroom.

TABLE C1 (*Continued*)

Dimension/Score	Definition
High	The teacher delivered at least one lesson where she or he either: (1) attended to student thinking in a sophisticated way by purposefully selecting particular students to share their work and/or sequencing students' responses in a meaningful way or (2) vested intellectual authority in students' mathematical reasoning throughout a lesson and did not base judgments of correctness on the teacher or text. Additionally, the teacher delivered no lessons or only one lesson where she or he did not attend to student thinking at all and vested intellectual authority in the teacher or text only.

Notes

This work was supported from a grant from the National Science Foundation (IERI grant REC-0228343). The content and opinions expressed herein do not necessarily reflect the views of the National Science Foundation or any other agency of the US Government. We wish to thank Marc Chun, Teresa McCaffrey, Rebecca McGraw, Chris Nelson, Laurie Rubel, Marcia Seeley, Jaime Smith, Sarah Spencer, Stephanie Sutherland, Mikyung Wolf, and Bahadir Yanik for help with data collection. We would also like to thank Kristine Acosta, Linda Choi, Amy Hillen, LuAnn Malik, Willow Mata, Andrea Miller, Wanda Nieters, Darlene Poluan, Marsha Seeley, Jaime Smith, and Stephanie Sutherland for help with data analysis and Deanna Weber Prine for assistance preparing the document. Thanks to Bill Penuel and Min Sun for sharing their analysis of their measures of depth and expertise. We are also grateful to Charles Ragin for his advice on interpreting the findings from our QCA analysis. Finally, we extend our gratitude to all the participants in this study for permitting us into their schools and offices and allowing us to interview and observe them engaged in their instructional improvement efforts.

1. Because of space limitations, a methodological appendix (app. D) accompanies the online version of this article. The appendix provides additional detail on sampling, measures, and interrater reliability.

2. The name of the district, schools, and teachers are pseudonyms.

3. Our research collaborators administered a survey to all teachers in case study schools in spring 2005 and spring 2006, years 2 and 3 of our study. However, the survey, intended to serve another branch of the research project, was designed to support school-level analysis rather than analysis of focal teachers' social networks. Thus, it did not include a full social network protocol or attention to most of the dimensions of interest in the present study. Therefore, we only used survey data to validate and extend our interview and observational data.

4. While we collected data in the fall and spring of years 2 and 3, we only collected data in spring of year 1. Given that year 1 was the first year that 11 out of 12 focal teachers were using the *Investigations* materials, it is likely that scores for instructional quality were lower in the fall and higher in the spring as teachers grew more accustomed to this new approach to mathematics instruction. Thus, by only collecting observational data in the spring of year 1, it is possible that our year 1 measures of instructional quality are biased upward. However, it is not likely that this potential bias affected our overall findings because we found no relationship between year 1 quality of instruction and sustainability in year 3. If we found no relationship with what are possibly inflated scores in year 1, it seems unlikely that we would find a relationship if the scores were lower given that one would expect that higher scores in year 1 would be associated with sustainability in year 3, not lower scores.

5. For two tasks, teachers chose lessons from the text that contained "no mathematical activity." For example, in one case, a teacher had students collecting data in response to a question that they would represent graphically in subsequent lessons. For such tasks, there was no cognitive demand to be maintained, and we therefore did not include a cognitive demand score from that lesson in our calculations.

6. It is true, as one anonymous reviewer pointed out, that there were no teachers

in our sample who had all three network conditions in year 1 who did not have access to a high level of expertise in year 2. However, *fs*QCA has a procedure for incorporating what they call "logical remainders" (e.g., configurations in which there are no empirical observations) into the model using counterfactual analysis. Thus, the QCA considers the range of outcomes possible if there were empirical cases with a wider variety of configuration of causal conditions than available in the sample. The analysis essentially runs multiple models incorporating potential outcomes from different configurations of conditions as it engages in Boolean minimization, thus taking into account a broader range of possible configurations of conditions. It is important to note that in doing this analysis, *fs*QCA permits the analyst to enter a range of assumptions to guide the counterfactual analysis; we used the most conservative set of assumptions possible.

References

Adler, Paul S., and Seok-Woo Kwon. 2002 "Social Capital: Prospects for a New Concept." *Academy of Management Journal* 27 (1): 17–40.

Ball, Deborah L. 1990. "The Mathematical Understandings That Prospective Teachers Bring to Teacher Education." *Elementary School Journal* 90 (4): 449–66.

Berends, Mark, Susan J. Bodilly, and Sheila Nataraj Kirby. 2002. *Facing the Challenges of Whole-School Reform: New American Schools after a Decade*. Santa Monica, CA: RAND.

Bidwell, Charles E., and Jeffrey Yasumoto. 1999. "The Collegial Focus: Teaching Fields, Collegial Relationships, and Instructional Practice in American High Schools." *Sociology of Education* 72 (4): 234–56.

Borgatti, Stephen P., and Pacey C. Foster. 2003. "The Network Paradigm in Organizational Research: A Review and Typology." *Journal of Management* 29 (6): 991–1013.

Borgatti, Stephen P., and Brandon Ofem. 2010. "Overview: Social Network Theory and Analysis." In *Social Network Theory and Educational Change*, ed. Alan J. Daly. Cambridge, MA: Harvard Education Press.

Brendefur, Jonathan, and Jeffrey Frykholm. 2000. "Prompting Mathematical Communication in the Classroom: Two Preservice Teachers' Conceptions and Practices." *Journal of Mathematics Teacher Education* 3 (2): 125–53.

Bryk, Anthony, Penny Sebring, Elaine Allensworth, Stuart Leppescu, and John Easton. 2010. *Organizing Schools for Improvement: Lessons from Chicago*. Chicago: University of Chicago Press.

Carrasco, Juan A., Bernie Hogan, Barry Wellman, and Eric J. Miller. 2006. "Collecting Social Network Data to Study Social Activity-Travel Behavior: An Egocentric Approach." Paper presented at the eighty-fifth Transportation Research Board meeting, January, Washington, DC.

Centola, Damon. 2010. "The Spread of Behavior in an Online Social Network Experiment." *Science* 329 (5996):1194–97.

Cobb, Paul, Koeno Gravejeijer, Erna Yackel, Kay McClain, and Joy Whitenack. 1997. "Mathematizing and Symbolizing: The Emergence of Chains of Signification in One First-Grade Classroom." In *Situated Cognition: Social, Semiotic, and Psychological Perspectives*, ed. David Kirschner and James A. Whitson. Mahwah, NJ: Erlbaum.

Coburn, Cynthia E. 2001. "Collective Sensemaking about Reading: How Teachers Mediate Reading Policy in Their Professional Communities." *Educational Evaluation and Policy Analysis* 23 (2): 145–70.

Coburn, Cynthia E. 2003. "Rethinking Scale: Moving beyond Numbers to Deep and Lasting Change." *Educational Researcher* 32 (6): 3–12.

Coburn, Cynthia E., Willow Mata, and Linda Choi. 2012. "The Embeddedness of Teachers' Social Networks: Evidence from Mathematics Reform." Unpublished manuscript, University of California, Berkeley.

Coburn, Cynthia E., and Jennifer Lin Russell. 2008. "District Policy and Teachers' Social Networks." *Educational Evaluation and Policy Analysis* 30 (3): 203–35.

Coleman, James S. 1988. "Social Capital in the Creation of Human Capital." *American Journal of Sociology* (suppl.: "Organizations and Institutions: Sociological and Economic Approaches to the Analysis of Structure") 94:S95–S120.

Cooper, Robert, Robert E. Slavin, and Nancy A. Madden. 1998. "Success for All: Improving the Quality of Implementation of Whole-School Change through the Use of a National Reform Network." *Education and Urban Society* 30 (3): 385–408.

Cuban, Larry. 1988. "Constancy and Change in Schools (1880s to the Present)." In *Contributing to Educational Change*, ed. Phillip Jackson. Berkeley, CA: McCutchan.

Cuban, Larry. 1993. *How Teachers Taught: Constancy and Change in American Classrooms*. 2nd ed. New York: Teachers College Press.

Datnow, Amanda, Lea Hubbard, and Hugh Mehan. 2002. *Extending Educational Reform: From One School to Many*. London: Routledge/Falmer.

Davis, Gerald. F. 1991 "Agents without Principles? The Spread of the Poison Pill through the Inter-corporate Network." *Administrative Science Quarterly* 36 (4): 583–613.

DiMaggio Paul, and Hugh Louch. 1998. "Socially Embedded Consumer Transactions: For What Kinds of Purchases Do People Most Often Use Networks?" *American Sociological Review* 63 (5): 619–37.

Doyle, Walter. 1983. "Academic Work." *Review of Educational Research* 53 (2): 159–99.

Elmore, Richard F., and Deanna Burney. 1999. "Investing in Teacher Learning: Staff Development and Instructional Improvement." In *Teaching as the Learning Profession: Handbook of Policy and Practice*, ed. Linda Darling-Hammond and Gary Sykes. San Francisco: Jossey-Bass.

Frank, Kenneth. A., Chong Min Kim, and Dale Belman. 2010. "Utility Theory, Social Networks, and Teacher Decision Making: Modeling Networks' Influences on Teacher Attitudes and Practices." In *Social Network Theory and Educational Change*, ed. Alan J. Daly. Cambridge, MA: Harvard Educational Press.

Frank, Kenneth A., Yong Zhao, and Kathyrn Borman. 2004. "Social Capital and the Diffusion of Innovations within Organizations: The Case of Computer Technology in Schools." *Sociology of Education* 77 (2): 148–71.

Gersten, Russell, David Chard, and Scott Baker. 2000. "Factors Enhancing Sustained Use of Research-Based Instructional Practices." *Journal of Learning Disabilities* 33 (5): 445–56.

Hansen, Morten T. 1999. "The Search-Transfer Problem: The Role of Weak Ties in Sharing Knowledge across Organization Subunits." *Administrative Science Quarterly* 44 (1): 82–111.

Hargreaves, Andy, and Dean Fink. 2000. "The Three Dimensions of Reform." *Educational Leadership* 57 (7): 30–34.

Hargreaves, Andy, and Ivor Goodson. 2006. "Educational Change over Time? The Sustainability and Nonsustainability of Three Decades of Secondary School Change and Continuity." *Educational Administration Quarterly* 42 (1): 3–41.

Henningsen, Marjorie, and Mary Kay Stein. 1997. "Mathematical Tasks and Student Cognition: Classroom-Based Factors That Support and Inhibit High-Level Mathematical Thinking and Reasoning." *Journal for Research in Mathematics Education* 28 (5): 524–49.

Hightower, Amy M., Michael S. Knapp, Julie A. Marsh, and Milbrey W. McLaughlin. 2002. *School Districts and Instructional Renewal.* New York: Teachers College Press.

Horn, Ilana Seidel, and Judith Warren Little. 2010. "Attending to Problems of Practice: Routines and Resources for Professional Learning in Teachers' Workplace Interactions." *American Educational Research Journal* 47 (1): 181–217.

Johnson, Knowlton, Carol Hays, Hayden Center, and Charlotte Daley. 2004. "Building Capacity and Sustainable Prevention Innovations: A Sustainability Planning Model." *Evaluation and Program Planning* 27 (2): 135–49.

Johnson, Susan Moore, Jill Harrison Berg, and Morgaen L. Donaldson. 2005. *Who Stays in Teaching and Why: A Review of the Literature on Teacher Retention.* Cambridge, MA: Harvard Graduate School of Education.

Kilduff, Martin, and Daniel J. Brass. 2010. "Organizational Social Network Research: Core Ideas and Key Debates." In *Academy of Management Annuals*, vol. 4, ed. J. P. Walsh and A. P. Brief. New York: Routledge.

Klingner, Janette K., Sharon Vaughn, Marie Tejero Hughes, and Maria Elena Arguelles. 1999. "Sustaining Research-Based Practices in Reading: A 3-Year Follow-Up." *Remedial and Special Education* 20 (5): 263–74, 287.

Lampert, Magdalene. 1990. "When the Problem Is Not the Question and the Solution Is Not the Answer: Mathematical Knowing and Teaching." *American Educational Research Journal* 27 (1): 29–63.

Lampert, Magdalene. 2001. *Teaching Problems and the Problems of Teaching.* New Haven, CT: Yale University Press.

Lin, Nan. 2000. "Inequality in Social Capital." *Contemporary Sociology* 29 (6): 785–95.

Little, Judith Warren. 1982. "Norms of Collegiality and Experimentation: Workplace Conditions of School Success." *American Educational Research Journal* 19 (3): 325–40.

Little, Judith Warren. 1990. "The Persistence of Privacy: Autonomy and Initiative in Teachers' Professional Relations." *Teachers College Record* 91 (4): 509–36.

Loeb, Susanna, and Michelle Reininger. 2004. *Public Policy and Teacher Labor Markets: What We Know and Why It Matters.* East Lansing: Education Policy Center, Michigan State University.

Lortie, Dan C. 1975. *Schoolteacher: A Sociological Study.* Chicago: University of Chicago Press.

Louis, Karen S., and Helen M. Marks. 1998. "Does Professional Community Affect the Classroom? Teachers' Work and Student Experience in Restructuring Schools." *American Journal of Education* 106 (4): 532–75.

Ma, Liping. 1999. *Knowing and Teaching Elementary Mathematics: Teachers' Understanding of Fundamental Mathematics in China and the United States.* New York: Routledge.

Mac Iver, Martha Abele, and Elizabeth Farley. 2003. "Bringing the District Back In: The Role of the Central Office in Improving Instruction and Student Achievement." Report 65, Center for Research on the Education of Students Placed at Risk, Baltimore.

Marsh, Julie A., Kerri A. Kerr, Gina S. Ikemoto, Hilary Darilek, Marika Suttorp, Ron W. Zimmer, and Heather Barney. 2005. *The Role of Districts in Fostering Instructional Improvement: Lessons from Three Urban Districts Partnered with the Institute for Learning.* Santa Monica, CA: RAND Education.

McLaughlin, Milbrey W., and Dana Mitra. 2001. "Theory-Based Change and Change-Based Theory: Going Deeper and Going Broader." *Journal of Educational Change* 2 (4): 301–23.

National Council of Teachers of Mathematics. 1989. *Curriculum and Evaluation Standards for School Mathematics.* Reston, VA: National Council of Teachers of Mathematics.

National Council of Teachers of Mathematics. 2000. *Principles and Standards for School Mathematics*. Reston, VA: National Council of Teachers of Mathematics.

Obstfeld, David. 2005. "Social Networks, the *Tertius Lungens* Orientation, and Involvement in Innovation." *Administrative Science Quarterly* 50 (1): 100–130.

Penuel, William R., Kenneth A. Frank, and Ann E. Krause. 2010. "Between Leaders and Teachers: Using Social Network Analysis to Examine the Effects of Distributed Leadership." In *Social Network Theory and Educational Change*, ed. Alan J. Daly. Cambridge, MA: Harvard Educational Press.

Penuel, William R., Margaret Riel, Ann E. Krause, and Kenneth A. Frank. 2009. "Analyzing Teachers' Professional Interactions in a School as Social Capital: A Social Network Approach." *Teachers College Record* 111 (1): 124–63.

Post, Thomas R., Guershon Harel, Merlyn J. Behr, and Richard Lesh. 1991. "Intermediate Teachers' Knowledge of Rational Number Concepts." In *Integrating Research on Teaching and Learning Mathematics*, ed. Elizabeth Fennema, Thomas P. Carpenter, and Susan J. Lamon. Albany, NY: SUNY Press.

Ragin, Charles C. 1987. *The Comparative Method: Moving beyond Qualitative and Quantitative Strategies*. Berkeley: University of California Press.

Ragin, Charles C. 2008. *Redesigning Social Inquiry: Fuzzy Sets and Beyond*. Chicago: University of Chicago Press.

Reagans, Ray, and Bill McEvily. 2003. "Network Structure and Knowledge Transfer: The Effects of Cohesion and Range." *Administrative Science Quarterly* 48 (2): 240–67.

Rihoux, Benoit, and Charles C. Ragin, eds. 2009. *Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques*. Thousand Oaks, CA: Sage.

Rivera, Mark T., Sara B. Soderstrom, and Brian Uzzi. 2010. "Dynamics of Dyads in Social Networks: Assortive, Relational, and Proximity Mechanisms." *Annual Review of Sociology* 36:91–115.

Smith, Margaret S. 2000. "Balancing Old and New: An Experienced Middle School Teacher's Learning in the Context of Mathematics Instructional Reform." *Elementary School Journal* 100 (4): 351–75.

Snipes, Jason, Fred Doolittle, and Corinne Herlihy. 2002. *Foundations for Success: Case Studies of How Urban School Systems Improve Student Achievement*. Washington, DC: Council of Great City Schools.

Spillane, James P., and Nancy E. Jennings. 1997. "Aligned Instructional Policy and Ambitious Pedagogy: Exploring Instructional Reform from the Classroom Perspective." *Teachers College Record* 98 (3): 449–81.

Spillane, James P., and John S. Zeuli. 1999. "Reform and Teaching: Exploring Patterns of Practice in the Context of National and State Mathematics Reform." *Educational Evaluation and Policy Analysis* 21 (1): 1–27.

Stein, Mary Kay, Randi A. Engle, Margaret S. Smith, and Elizabeth K. Hughes. 2008. "Orchestrating Productive Mathematical Discussions: Five Practices for Helping Teachers Move beyond Show and Tell." *Mathematical Thinking and Learning* 10 (4): 313–40.

Stein, Mary Kay, Barbara W. Grover, and Marjorie Henningsen. 1996. "Building Students Capacity for Mathematical Thinking and Reasoning: An Analysis of Mathematical Tasks Used in Reform Classrooms." *American Educational Research Journal* 33 (2): 455–88.

Stein, Mary Kay, Julia H. Kaufman, and M. Tekkumru-Kisa. 2011. "Curriculum as a Lever for Teacher Improvement." In *Proceedings of the 35th Conference of the International Group for the Psychology of Mathematics Education*, vol. 1. Ankara, Turkey: International Group for the Psychology of Mathematics Education.

Stein, Mary Kay, and Gooyeon Kim. 2009. "The Role of Mathematics Curriculum

Materials in Large-Scale Urban Reform: An Analysis of Demands and Opportunities for Teacher Learning." In *Teachers' Use of Mathematics Curriculum Materials: Research Perspectives on Relationships between Teachers and Curriculum*, ed. Janine Remillard, Gwendolyn Lloyd, and Beth Herbel-Eisenmann. New York: Routledge.

Stein, Mary Kay, and Suzanne Lane. 1996. "Instructional Tasks and the Development of Student Capacity to Think and Reason: An Analysis of the Relationship between Teaching and Learning in a Reform Mathematics Project." *Educational Research and Evaluation* 2 (1): 50–80.

Strauss, Anselm, and Juliet Corbin. 1990. *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Newbury Park, CA: Sage.

Sun, Min, Kenneth A. Frank, Annie Garrison, Paul Cobb, and Thomas Smith. 2011. "The Use of Multilevel Item Response Theory Modeling to Estimate Professional Interactions among Teachers." Paper presented at the annual American Educational Research Association conference, New Orleans, April.

TERC. 2011. "Investigations in Number, Data, and Space: Overview of Investigations," http://investigations.terc.edu/library/developing/overview.cfm.

Tyack, David, and Larry Cuban. 1995. *Tinkering toward Utopia: A Century of Public School Reform*. Cambridge, MA: Harvard University Press.

Uzzi, Brian. 1996. "The Sources and Consequences of Embeddedness for the Economic Performance of Organizations: The Network Effect." *American Sociological Review* 61 (4): 674–98.

Uzzi, Brian. 1997. "Social Structure and Competition in Interfirm Networks: The Paradox and Embeddedness." *Administrative Science Quarterly* 42 (1): 35–67.

Uzzi, Brian. 1999. "Embeddedness in the Making of Financial Capital: How Social Relations and Networks Benefit Firms Seeking Financing." *American Sociological Review* 64 (4): 481–505.

Uzzi, Brian, and Ryon Lancaster. 2003. "Relational Embeddedness and Learning: The Case of Bank Loan Managers and Their Clients." *Management Science* 49 (4): 383–99.

Valente, Thomas W. 1995. *Network Models of the Diffusion of Innovations*. Cresskill, NJ: Hampton.

Wellman, Barry, and S. D. Berkowitz. 1988. *Social Structures: A Network Approach*. New York: Cambridge University Press.

Yasumoto, Jeffrey Y., Kazuaki Uekawa, and Charles E. Bidwell. 2001. "The Collegial Focus and High School Students' Achievement." *Sociology of Education* 74 (3): 181–209.