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PERSPECTIVE

Shrouded in Structure: Challenges and Opportunities for a Friction-Based View of Network Research

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Whereas network ideas and approaches have become prominent in both the managerial and sociological literatures, we contend that the increasing emphasis on network structures and their evolution has distracted us from the important issue of whether and when networks actually work in the ways that our theories assume. In particular, we explore the well-established assumption that knowledge flows over network paths, with special attention to the role of friction when the supposed information transfer spans multiple dyads. Our analysis shows that friction is omnipresent and has implications at both the system and subsystem levels. More specifically, we present a rich set of research opportunities that addresses implications of friction for the variation of knowledge flows for different network structures and also for the distribution of knowledge among the actors within a particular network.

Keywords: interorganizational networks; friction; network structure; knowledge transfer
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Introduction

Social network research has witnessed exponential growth, dramatically increasing our understanding of how relations among actors shape their behaviors and outcomes. With this growth, the scope of relations assumed to affect an actor has widened from direct ties conferring resource exchange (e.g., Coleman et al. 1957) to broader views of position that incorporate ties beyond an actor's direct connection, exemplified by the embeddedness and social capital perspectives (e.g., Burt 1992, Coleman 1990, Granovetter 1985). This trend of incorporating relational and systemic views of organizational phenomena rather than just reductionist and atomistic explanations (see Borgatti and Foster 2003, Borgatti et al. 2009) has been accelerated by the ever-growing sources of systematic network data and the corresponding computing capabilities to analyze these data convincingly. In turn, the availability of such detailed longitudinal network data has given rise to studies that borrow from the physical sciences to focus on universal patterns in network analysis, such as the structure and evolution of networks themselves (Borgatti et al. 2009).

Podolny (2001) has noted that there are two distinct ways by which networks affect outcomes. The "networks as pipes" perspective treats ties as resource conduits that resolve uncertainty for the focal actors, whereas the "networks as prisms" perspective treats ties as indicators of status that resolve uncertainty for others in their evaluation of focal actors. Both perspectives have made important contributions to the literature; however, we focus on the "pipes" approach, as our interest is in evaluating knowledge flows in networks. More specifically, in this paper we trace how assumptions about knowledge flows in networks have evolved concomitantly with the increasing emphasis on broader structural views of networks.

The key contribution of this paper is the consideration of "frictions" that temper knowledge flows in networks. We contend that although a host of literature addresses the challenges of transmitting knowledge between actors effectively (e.g., Hansen and Haas 2001, Szulanski 1996), the burgeoning structuralist perspectives in the network literature have underaddressed these issues in networks, providing a fertile context for a new wave of network research. Of course, we wish to direct researchers' attention to the pervasiveness of frictions in networks; however, it is important to note that although such frictions may preclude the transfer of relevant knowledge, they may also help network functioning by reducing information overload. Our aim is to emphasize a "friction-based view" in our network research that explicates friction's effects through both empirical examination and modeling. Importantly, the issues we raise apply to both interpersonal and interorganizational networks. Given that interorganizational ties are typically some composite of interpersonal relationships, we take advantage of the variety of interorganizational ties to assess how frictions arise differentially across interorganizational networks derived from alliances, employee mobility, or common affiliations.

The rest of our paper proceeds in three sections. First, we summarize the trends in the literature on knowledge flows in networks, arguing that an implicit assumption of largely unrestricted knowledge flow underlies much of this work. Second, we address how frictions have been consistently demonstrated among pairs of actors in neighboring fields of research, and we consider how these frictions are likely to aggregate among the many pairs of actors composing a network. Finally, we identify key areas in which future research should integrate this friction-based view to improve our understanding of knowledge variation and related outcomes both within and across networks.

How Has the Role of Knowledge Flows Evolved in Organizational Research on Networks?

From Individual to Organizational Actors

Until the last two decades, the primary emphasis of social network studies was how network ties between individuals determined behaviors, attitudes, and outcomes. Thus, numerous intensive sociometric data collection efforts yielded matrices of instrumental (e.g., work advice, discussion) and/or affective (e.g., friendship) ties between individuals, which were then associated with behaviors such as innovation adoption (Coleman et al. 1957, Ibarra 1992) or power use (Burkhardt and Brass 1990, Krackhardt 1990), attitudes such as job satisfaction (Krackhardt and Porter 1985), and outcomes such as promotion or mobility (Burt 1992, Podolny and Baron 1997). Of course, the primary mechanism by which these ties were associated with these varied activities has been the transmission of information or knowledge across the ties. These knowledge flows (including resources such as technical information, referrals, and rumors) have been assumed to provide differential benefits to individuals depending on their position in the social network(s) of interest.

The 1990s, however, experienced a sharp rise in the preponderance of interorganizational network studies, where the actor of interest was typically a firm rather than an individual. The reasons for this transition are simultaneously conceptual and empirical: Powell's (1990) seminal chapter on "network forms of organization" (p. 295) extended Granovetter's (1985) earlier work on embeddedness at a time when, for example, alliances were becoming a legitimized form of interorganizational cooperation. Concomitantly, data sources to construct interorganizational ties became more accessible (for example, SDC Platinum for alliances, the U.S. Patent and Trademark Office records for knowledge transfer, Compact Disclosure for director interlocks), which enabled the construction of ever more complete and voluminous networks.

Despite this shift in level of analysis, much of the reasoning about network position and knowledge flows was comparable to the studies of intraorganizational networks, suggesting that network position would determine firm behaviors such as alliance formation (Gulati 1995, Gulati and Gargiulo 1999) and innovation adoption (Westphal et al. 1997) and firm outcomes such as innovative performance (Ahuja 2000, Powell et al. 1996) and firm survival (Uzzi 1997). This anthropomorphization of organizations is endemic in the behavioral tradition (Denrell et al. 2004, March and Simon 1958) as well as in the strategy literature's knowledge-based view (Grant 1996, Winter 1987), which has influenced interorganizational researchers to attribute individually oriented behaviors (such as communication or learning) to organizations.

Consideration of Broader Network Structures

A second shift in the nature of social network research arose in the late 1990s. With the advent of high computational power, the rise of network analysis in the physical sciences enabled the development of key models of network structure, such as scale-free and small-world models (Barabási and Albert 1999, Watts and Strogatz 1998). These models shaped research activity in a variety of disciplines, as researchers sought to identify applications of these structures in their own fields. Furthermore, the availability of better longitudinal network archival data has fueled studies of the evolution of these structures—a crucial research objective in the effort to mimic our counterparts in the physical sciences (Borgatti et al. 2009). Unfortunately, these trends have led us to neglect the underlying mechanisms shaping these networks and advantaging or disadvantaging firms (Gulati et al. 2011). Indeed, over this time period, macro-organizational scholars followed these trends in the physical sciences more quickly, most likely because the interorganizational networks generated from larger, longitudinal archival data were more amenable to these models from the physical sciences than the smaller networks generated by intraorganizational sociometric data.[1]

To delve more deeply into one example, the "small-world" formalization of Watts and Strogatz (1998) has captivated many audiences because this network structure seems better suited to efficient search and diffusion than other well-established structures (Schilling and Phelps 2007, Verspagen and Duysters 2004, Watts 1999). As a result, it has launched research in many fields that embody network phenomena, and the organization theory literature is no exception. Here, a *small-world* network is taken to mean a network that simultaneously obtains high clustering and low path length.[2]

Empirical research examining the existence, evolution, and performance of these small worlds has flourished in our literature. Initially, efforts documented the *existence* of small-world networks for a variety of interorganizational network ties, including corporate ownership (Kogut and Walker 2001), board interlocks (Davis et al. 2003), investment bank syndicates (Baum et al. 2003), and alliance networks (Verspagen and Duysters 2004). Through longitudinal methods, several of these papers also examined the *evolution* of these small-world networks, demonstrating their emergence and stability and asserting that they are reliable conduits of information that persist over time in spite of exogenous disruptions such as globalization, turnover, and restructuring (e.g., Baum et al. 2003, Davis et al. 2003, Kogut and Walker 2001). The simultaneous existence of high clustering and low path length in small-world networks implies that shortcuts, or bridging ties, can be identified between the more densely connected clusters in these networks. Thus, several papers have also leveraged this structural variety in small worlds, discriminating between network ties that generate shortcuts and those that exist within clusters (e.g., Baum et al. 2003, Gulati et al. 2012, Rosenkopf and Padula 2008).

Importantly, this focus on identification and evolution of small worlds skirts the question of how such structures, by shaping knowledge flows, affect the performance of actors or systems. A much smaller set of papers has examined this issue, and the results are equivocal. Uzzi and Spiro (2005) examine collaboration networks for Broadway musicals, demonstrating an inverted U-shaped relationship between small-world network characteristics and revenue. In contrast, Fleming et al. (2007) and Fleming and Marx (2006) find no relationship between the small-world characteristics of inventor collaboration networks and regional patent productivity. Schilling and Phelps (2007) examine alliance networks across multiple industries and argue that the more a firm was embedded in an industry-wide alliance network with high clustering and short average path lengths (reach), the more likely it was to gain access to knowledge important for innovation. They find that the interaction of clustering and reach in industry alliance networks was positively associated with firm patent productivity. These discrepancies in findings across studies are largely unresolved; they may be attributable to the variation in performance measures across studies, the putative mechanisms by which the small worlds are affecting this performance measure, or other differences in industry or tie context between the networks under examination.

From Dyads to Longer Paths

The emphasis on network structures during the 1990s grew alongside an increasing interest in alliances and other interorganizational ties in the strategic management literature. Here, researchers examined empirically whether knowledge was actually transmitted within dyads. Thus, both alliances and mobility were demonstrated to transfer knowledge (Mowery et al. 1996). The natural confluence of the network literature and the knowledge-based view in strategic management spawned a flourishing stream of literature that, we argue, implicitly generalized the dyadic flows of simple behaviors, practices, and contagions to a more general flow of information and knowledge within the network. For example, Powell et al. (1996) argue that the locus of learning in industries with complex knowledge bases and uncertainty shifts from individual firms to networks, which makes an implicit assumption of knowledge flows beyond the dyad. Their initial claim that "firms must learn how to transfer knowledge across alliances" (Powell et al. 1996, pp. 119–120) is clearly consistent with dyadic flows. Yet they shortly assert that "R&D [research and development] collaboration is both an admission ticket to an information network and a vehicle for the rapid communication of news about opportunities and obstacles" (Powell et al. 1996, p. 120), which intimates extensive flows of knowledge beyond individual dyads in the service of innovation across the network. Similarly, Gulati (1999, p. 398) claims that "although strategic alliances are essentially dyadic exchanges, key precursors, processes, and outcomes associated with them can be defined and shaped by the networks…," which also alludes to spillovers beyond the dyad. Additionally, Ahuja (2000) demonstrates that indirect (that is, multistep) alliance ties are associated with firm innovation output, suggesting that the flow of knowledge over these indirect ties increases knowledge access.

This leap from dyadic knowledge flows to longer flows along linked paths is endemic in the research on small-world networks. The claim that small worlds are efficient structures for diffusion and search rests on the assumption that the phenomenon of interest flows between clusters via shortcuts, because shortcuts (bridges between clusters) dramatically shorten path length. In other words, for small worlds to transmit effectively, the nodes that bridge to other clusters must freely transmit their knowledge.

Two more recent simulations identify useful constraints to the effectiveness of small world structures. Lazer and Friedman (2007), examining organization and system-level learning, demonstrate that the small world diffuses information more quickly but that this property of quick information diffusion actually drowns out superior solutions that emerge more slowly. Thus the small world generates the highest short-term performance but weaker long-term performance. This demonstration, however, again rests on the assumption of unrestricted knowledge flows occurring over multistep paths. In contrast, Centola and Macy (2007) examine "complex contagions" where more than one source is required to ratify knowledge; with this constraint, small worlds are less effective than other network structures because the effect of shortcuts is dramatically attenuated.

Although the elegance of the small world structure is alluring, it is intriguing to note that even in the well-known original letter-forwarding experiment that introduced the concepts of small worlds and "six degrees of separation," 78% of the letters never were forwarded to the intended destination (Travers and Milgram 1969), suggesting significant constraints on knowledge flows. More relevant to organizations and knowledge flows, research on the knowledge-based view emphasizes firm heterogeneity as a crucial determinant of organizational performance (Grant 1996, Winter 1987). This heterogeneity obtains because organizational actors are neither passive elements nor atomistic units that allow transparent knowledge diffusion; rather, they are likely to distort knowledge flows as a function of their own volition and also of the structure in which they are embedded.

Assumptions About Knowledge Flows in Network Research Discount Frictions

A thorough appreciation of knowledge flows in networks, however, needs to acknowledge the many forces that counterbalance the putative flows we have discussed. Friction is generally defined as the resistance that one surface or object encounters when moving over another. In our specific case, the object is knowledge, which moves dyadically from node to node over the network via ties. The probability of knowledge transmission, then, will be affected by four properties of this system: (1) the characteristics of nodes composing dyads, (2) the broader structure of the network in which the dyads are embedded, (3) the types of ties composing the network, and (4) the nature of the knowledge to be transmitted. We discuss each of these properties in turn.

Sources of Friction in Dyads

Most simply, we can consider friction in knowledge flows between two linked nodes. Szulanski's (1996) work on "knowledge stickiness" (that is, when knowledge does not flow effectively between parties) suggests sources of friction that are related to each of the sending and receiving nodes. Let us first consider the *receiving* node. Any node with the potential to receive information may be more or less likely to attend to or to comprehend and process this information. Szulanski suggests that knowledge can be sticky as a result of either a node's lack of motivation or its inability to absorb or retain the knowledge. Hansen and Haas (2001) assert that a node's reception of knowledge can be influenced by the volume of knowledge available to it, suggesting that nodes have some sort of carrying capacity beyond which additional information cannot be attended to or received accurately. As another example, Centola and Macy (2007) suggest that nodes may require confirming information (i.e., checking for its reliability) from more than one source before acting upon it and that the threshold number of sources required can vary by node. In sum, even for the transmission of basic information bits, friction at nodes may vary because of their inherent capacity limitations or their ability to reliably process the information.

Paralleling this approach for any node *sending* information, Szulanski (1996) also posits that stickiness arises when the source node has a lack of motivation or is perceived as unreliable. In a model of organization learning over networks, Schilling and Fang (2014) model how hubs (that is, high-profile nodes) may "forget, lie, and play favorites." For example, under weak appropriability regimes, firms utilize secrecy to appropriate gains from innovations as opposed to patenting and thus revealing their knowledge (Cohen et al. 2000, Levin et al. 1987). Similarly, Borgatti and Cross (2003) demonstrate that potential recipients will be deterred from knowledge-seeking when they perceive high costs associated with the transfer. As studies of alliance network dynamics suggest that more powerful firms appropriate knowledge from their less powerful partners through asymmetric deal structures (Ahuja et al. 2009), it is not surprising that less powerful firms fear these costs and seek other alternatives to gain knowledge.

Of course, even when the source and recipient are motivated and reliable, friction can occur in the transmission across the dyad. It is a basic premise of communication theory that there is some loss of fidelity along a link when information flows between two nodes. The analog to interpersonal communication is that even though two people seek to share information, some of it may be misunderstood as a result of unintentional error (spoken information is misheard or misinterpreted, for example).

Knowledge Complexity Increases Friction

The more complex or tacit the information to be transferred, the greater the sources of error. Szulanski (1996) demonstrates that complex knowledge is more sticky in his study of best practice transfer. Likewise, Hansen (1999) suggests that tacit information is not transmitted effectively over weak ties, where strength of the tie is defined as the frequency of interactions between two groups within a large multinational company. Similarly, Centola and Macy (2007) argue that confirmation from additional sources is required for "complex contagions," which reduces transmission probabilities.

Network Embeddedness of Dyads Increases Friction

Next, we extend our thinking to consider knowledge flows along the simplest multistep path, A–B–C. Here, for

Figure 1 Network Structure Where B Is a Hub

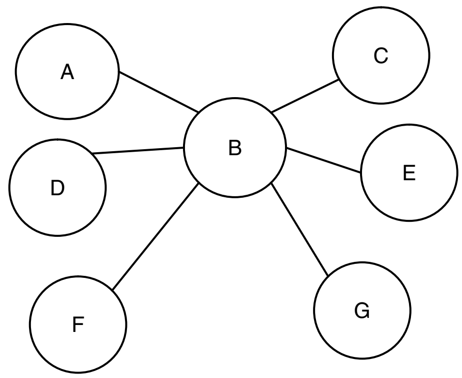
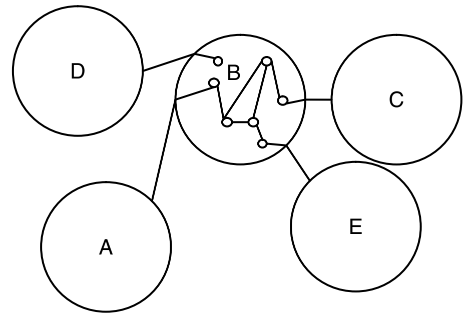


Figure 2 Network Structure Where B Is Not a Unitary Actor



knowledge to flow from A to C, it must be successfully communicated first from A to B and subsequently from B to C. So at a minimum, this transfer from A to C is more subject to attenuation since there are two links on which attenuation might occur. It is a simple extension of our discussion on friction in dyads to recognize that just because B receives the information from A does not imply that B will transmit it to C. B may not think it is relevant to C, B might forget to tell C, or B might prefer that C not know!

Considering the overall network structure rather than merely one chain through B suggests another important source of friction as well. Figure 1 displays an example that considers two additional chains, D–B–E and F–B–G. Each chain independently might be subject to the same frictions as discussed for A–B–C, but the aggregation of these three chains suggests that B needs to balance the competing demands of multiple network members. As a hub in the network, B can be subject to carrying capacity constraints as well. There may be limits to the number of different sources from which a hub can process information reliably and hence lead to bottlenecks in flows within the network (Zaheer and Usai 2004). Furthermore, a high degree (i.e., being a hub) is typically correlated with greater resources, status, and power (Rosenkopf and Schilling 2007, Stuart 1998), which may increase the likelihood of agentic action (i.e., consuming and withholding knowledge) even more.[3]

Several empirical studies demonstrate friction's effects on multistep transmission through individuals. In a study of inventive collaboration networks, Singh (2005) treats patents as nodes and common inventors between the patents as ties to explore citation patterns in patents. Whereas he found that the probability of citation between two patents linked by a common inventor was 4 times that of the likelihood of citation between unrelated patents, this likelihood decreased to 3.2 times for a two-step link and 2.7 times for a three-step link. Even more compelling was the result that patents linked by paths more than three steps were only 4% more likely to cite each other, suggesting that knowledge was not moving over longer paths. Similarly, Goel et al. (2012) examine diffusion patterns for seven different online services (such as Twitter News Stories and Yahoo! Voice) and demonstrate that the incidence of multistep transmissions was lower than traditional models of diffusion would suggest. Specifically, nearly 90% of diffusion paths concluded in one step, and these single-step paths accounted for 99% of all diffusion.

Yet in addition to the frictions that occur for A and B as senders and also for B and C as receivers, substantial additional friction can arise because of the important role B plays as the go-between in this chain. It is one thing to imagine B as a single individual in an interpersonal and/or intraorganizational network but quite another to imagine B as an organization in an interorganizational network. In this case, for the information to flow to B from A and then out from B to C, it is likely that different people in the organization would need to also accomplish an intraorganizational transfer of knowledge (Gulati et al. 2011, Phelps et al. 2012), as displayed in Figure 2. Such a transfer would actually increase the number of interpersonal steps needed to transfer the information; accordingly, attenuation could increase dramatically more than might be expected given a two-step transfer between organizations. This internal attenuation can represent a significant source of friction. Said differently, even if an organization has the motivation to share information it obtains from one relationship to other nodes with which it has relationships, it is not clear that this knowledge flows *intra*organizationally to facilitate this *inter*organizational transfer. In a study of inventor moves between organizations, Singh and Agrawal (2011) demonstrate that firms increase the use of prior inventions of new recruits by 219% on average; however, almost half of the increase is due to the sustained effect of the new recruit building on his or her own work rather than its spread to other inventors in the firm.

In addition, by implying that an organization "learns" or "spreads" or "stores" knowledge in a network, we aggregate the actions of many individuals and assume that the nodes are unitary actors in spite of the organizational structure or size. This is unrealistic in our context because an organizational "node" can actually represent a complex internal structure of individual (sub)actors that are the actual agents doing the learning, spreading, or storing (Simon 1991). The assumption that this intraorganizational network operates as a unitary node would imply that a multinational corporation with divisions spread across continents would have the same level of internal information flow among relevant parties as a small start-up, which is unlikely.

Friction Varies with Type of Interorganizational Tie

The variety of interorganizational ties that compose networks may be associated with different frictions. This is because the organizational members directly participating in the interorganizational ties may make up only a small fraction of the members of the organization, and participants within any organization may or may not come into contact with each other. Table 1 lists interorganizational ties ordered by the amount of friction that might be expected to arise given the demography and the activities of the participants. Director interlock ties, where one individual sits on the board for more than one company, have been demonstrated to diffuse managerial practices such as philanthropic behaviors (Galaskiewicz 1997), poison pills (Davis and Greve 1997), and total quality management (TQM) (Westphal et al. 1997). The relevant issue here is that the network tie is between two organizations, constituted by a single individual rather than any pairing of organizational personnel, so fewer interpersonal steps are required for knowledge transmission. This is not to say that friction is nonexistent, as it may arise due to individual motivation, but norms and practices regarding confidentiality are typically low in this setting since most interlocks represent cross-industry ties.

In contrast, interorganizational networks derived from alliance data, where ties are imputed as a result of two or more organizations participating in an alliance reported in a database such as SDC or Factiva, may be subject to much higher friction than those derived from director interlocks, given that only a select group of alliance team members interact (Ahuja et al. 2009). Whether the members share their knowledge with other alliance teams or whether there are processes of knowledge sharing within the organization will likely heighten or reduce intraorganizational knowledge transfer (Argyres and Silverman 2004, Leiponen and Helfat 2010).

Ties generated by joint technical committee participation are reasonably analogous to alliance ties. Technical committees offer a context where interpersonal trust develops through long-term repeated contact (Rosenkopf et al. 2001). As for alliance ties, knowledge transfer across multiple joint participation ties also depends on individuals sharing information with other technical committee participants across the organization. Finally, interorganizational networks constructed via mobility of personnel may be subject to even higher friction, because in addition to the challenge of information from the mobile employee spreading to others in the organization, the information must reach someone who subsequently moves in a timely fashion (Tzabbar 2009).

In summary, friction arises through a variety of sources, and the combined effects of nodal motivations, knowledge complexity, network structure, and tie type may yield very different transmission probabilities across varying network contexts. As an example, in information transmission where fidelity of content is not an important issue, such as rumors and gossip, friction may be lower than it would be for other transmissions where the reliability of the content is salient. Moreover, as the complexity of the knowledge being transmitted increases, the friction

Table 1 Friction in Interorganizational Ties

Tie type	What enables knowledge transmission in dyads	What precludes knowledge transmission in dyads	What enables knowledge transmission on multistep paths	Level of friction	Example
Director interlock	Common board member	Don't share info with both boards	Board members exposed to shared info must absorb it and share it with another board	Low	Davis and Greve (1997)
Alliance	Designated team members from both organizations	Competitive concerns	Team members must share with different team members in their organization	Medium	Ahuja et al. (2009)
Joint technical committee participation	Technical personnel from many organizations meet to share info	When companies are represented by different people, it is harder for interpersonal trust to develop	Technical personnel must forward info to other technical committee participants in an organization	Medium	Rosenkopf et al. (2001)
Mobility	Individual moves and carries knowledge; enduring social ties enable symmetric communication	Legal constraints such as nondisclosure agreements	Mobile individuals must move again, or knowledge must reach another individual in the organization who subsequently moves	High	Tzabbar (2009)

encountered likewise increases. Therefore, best practices such as TQM or poison pills are likely to encounter less resistance in propagating than a patented invention or a complex drug discovery process. This increase in friction for such complex information may rely not only on the tacit knowledge that must accompany it for accurate transmission but also on the type of tie needed to transfer this knowledge. It is likely that diffusion studies of managerial practices applicable across industries (such as poison pills or TQM) are common because of the role of the single-individual director interlocks that can shape these practices. In contrast, practices that might diffuse via alliance ties (such as the transfer of technical knowledge) may flow between organizations via alliance teams or mobility, but they may encounter much friction in moving through organizations internally in order to make their way to additional organizations through multistep alliance or mobility ties for the reasons we have discussed above. Ultimately, however, the key takeaway here is that the wide variety of frictions that can accumulate in networks may lead knowledge flows in these networks to be dramatically smaller than what one would expect given friction-free knowledge flows; this may help to explain the disparities in observed knowledge flow outcomes in networks.

Implications for Future Research

Elevating friction to the foreground of social network research promises to invigorate both our theorizing and our empirical findings. Such a friction-based view acknowledges that friction is omnipresent in networks, yet it varies in its impact as a result of the nodes, ties, and network structures under consideration. As researchers develop more empirical studies that directly measure friction (e.g., Goel et al. 2012, Singh 2005, Singh and Agrawal 2011), we can assess how friction varies across contexts. At the same time, complementary attention to generalizable techniques for estimating and modeling frictions can be initiated. These approaches are considered below by first addressing friction's subsystem-level implications (within networks) and subsequently addressing its system-level implications (across networks).

Analyzing Subsystem-Level Outcomes Within a Network Structure

Research that focuses on variations in knowledge outcomes among actors within a given network can yield insight into the frictions operating along nodes and ties. Inequality of outcomes can be correlated with various nodal characteristics that may proxy frictions, particularly in longitudinal studies. For example, via simulation, Reagans and Zuckerman (2008) posit that small worlds will increase outcome inequality among actors, as heterogeneity in degree distribution accentuates problems of information transfer capacity and motivation for balanced trade over time, which, in turn, lowers overall efficiency. Additionally, in an experimental study within an organization, Singh et al. (2010) show that the putative short path lengths operating in small worlds are activated differentially by organization members searching for relevant information: peripheral employees (in the structural sense as well as the demographic sense) tend to initiate their search paths to equally peripheral employees, who are not helpful in accessing information more readily available to key employees.

Some network-oriented studies have used survey methodologies to focus explicitly on particular characteristics that may be correlated with information transfer. For example, Borgatti and Cross (2003) develop a model for information seeking within an organization and then use a survey instrument to test their hypotheses about factors that enhance or inhibit information transfer. Reagans and McEvily (2003) aggregate their dyadic data to demonstrate that network-level factors such as social cohesion (constraint) and network range (diversity) operate beyond dyadic characteristics to facilitate knowledge transfer and hence reduce friction. Analogous research at the level of interorganizational networks can be more complex but should yield important findings. At the same time, insight can and should be drawn from other models, not explicitly network focused, that nonetheless incorporate frictions. For example, Rivkin (2001) finds knowledge complexity to be an important factor that influences knowledge replication and imitation. Future network studies should explicitly take into account such factors germane to frictions in information transfer.

Assessing System-Level Knowledge Flows over Varying Network Structures

Most of the research in the management domain that examines knowledge flows across overall systems uses agent-based models to compare performance outcomes. Modeling networks, agent-based or otherwise, enable the generation of data for a multitude of organizational situations and allow relative comparison of knowledge effects, albeit in an artificial setting. A promising opportunity for future research in this tradition arises by considering the implications of frictions on information flows, as well as the way these frictions operate differently depending on the presence or absence of hubs in networks. For example, Schilling and Fang (2014) suggest via simulation that learning is less effective in "very hubby" scale-free networks and more effective in "moderately hubby" networks. Given that many interorganizational networks demonstrate scale-free characteristics (Baum et al. 2004, Rosenkopf and Schilling 2007) and may therefore be considered very hubby, the role of hubs and any frictions associated with them is critical. Accordingly, Ghosh and Rosenkopf (2012) model network capacity under increasing friction and suggest that the more frictions are correlated with hubs, the greater the decrease in network capacity. Further work should also seek empirical data from field and experimental settings to validate and extend these ideas.

There are also ample opportunities for empirical work that compares networks across industries. For example, Rosenkopf and Schilling (2007) compare alliance networks across industries and note substantial differences in structure, some of which may be attributed to dissimilar levels of friction across industries with distinct appropriability regimes. Schilling and Phelps (2007) also compare alliance structures across industries to explain potential knowledge creation. Similar studies explicitly incorporating friction might help explain the inconsistencies in the literature on the effect of small-world structure on performance (Uzzi et al. 2007). These studies might also help to estimate latent friction parameters that may then be useful in other studies. At a minimum, they might help in research designs that meaningfully control for friction.

Understanding the effects of friction across different network structures may also benefit from importing models from related areas. A fruitful area of research in the social sciences in this spirit has been the application of concepts of information theory building on information processing limits and bounded rationality of agents (March and Simon 1958). For example, communication theory can be applied to account for the inertia in observed economic behavior. Using the hypothesis that individuals have limited information processing capacity, Sims (1998, 2003, 2006) argues that the path connecting market signals to individuals' behavioral reactions should have the characteristics of a finite-capacity channel, in the language of information theory, which explains the empirically observed delays in changes in prices and wages in any economy. Another application models the organization of firms as networks or hierarchies in a decision-theoretic model where managers are modeled as information processors and the efficiency of the structure is measured in terms of the number of processors and delay in processing (Radner 1993, Van Zandt and Radner 2001). These studies can serve as interesting exemplars for future work in our field.

Implications of Network Tie Selection and Measurement

Attention to differences in tie types and the multiplicity of ties between nodes can also bear on our understanding of knowledge flows. For example, a study that focuses on alliance ties alone raises the interesting question of whether other types of ties are likely to duplicate the knowledge structure. One might well expect that high-degree firms for one type of network tie are also prominent in networks where other ties are considered. At the same time, given that alliances and mobility to distant contexts tend to yield the greatest knowledge benefits because of their nonredundancy with other ties (Rosenkopf and Almeida 2003), it is plausible that networks made up of only one type of tie may underestimate connectivity. Indeed, in a pointed critique of the small-world literature, Grannis (2010) notes that the calculation of path length in networks is volatile for a host of data issues and emphasized how missing data might lead to distinctly different main components and hence a dramatically different system-level response.

Conclusion

The rapid growth of the literature on network structure has sharpened our understanding of tie formation and network evolution, but it has been less effective in discerning the varied outcomes of knowledge circulation within these networks. We contend that an important and underapplied area is the role of frictions that attenuate knowledge flows. Whereas frictions have been identified with regard to dyadic knowledge transmission and knowledge complexity, these findings are generally limited to subsystems of the network in which knowledge flows. In examining systemic knowledge transmission over networks, our field must do more to overcome the implicit assumption of knowledge circulating freely within interorganizational networks. Here, we have demonstrated that friction in network knowledge flows arises as a result of the agency and capabilities of nodes, the nature of knowledge to be circulated, and the overall structure and composition of network ties. Such an approach dovetails effectively with the recent call for a shift toward the understanding of microfoundations of network dynamics (Ahuja et al. 2011). As a result, we have identified several research opportunities to estimate and model frictions and to explore their effects in a variety of network contexts, and we look forward to a new wave of research that encompasses this friction-based view of networks.

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Endnotes

[1]In the past decade, however, the rise of big data on interpersonal ties (such as Facebook or LinkedIn connections) has been enabling similar work in the sociological domain, although less of this work explicitly considers organizational concerns. Very recent studies on intraorganizational ties (such as company emails or instant messages) are bringing these issues back into the domain of organizational behavior (e.g., Kleinbaum 2012).

[2]The Watts–Strogatz (1998) formulation is especially appealing to modelers because only a single parameter is needed to express the percentage of "shortcuts" between otherwise clustered actors. Thus, for a network of a given size and density, modelers

can vary this single parameter to observe the interim state of small-world structures between regular lattice and random network structures.

[3]Of course, some high-degree actors may obtain many connections as a result of roles such as promoters of open standards or centers of alliance clusters, in which case motives to withhold information may be reduced.

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