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Diffusion of innovations through social networks: Determinants and implications

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Abstract

Social scientists have long been interested in the diffusion of innovations—the process by which new ideas, behavior, and practices spread between persons, organizations, and even countries. While innovations can enter a community through various channels, ongoing spread of innovations through a community occurs through the medium of social networks—collections of interpersonal or digital relationships connecting actors to each other. Social networks are important for diffusion because relationships foster communication, trust, and flow of information. Diffusion outcomes are also shaped by the structural properties of social networks such as density, centrality, and strength of ties, as well as properties of the innovation and the actors involved in the process. The purpose of the article is twofold: (1) to take stock of the field and review ongoing debates on the role of social networks in the diffusion of innovations and (2) to summarize the sociological implications of the diffusion of innovations through social networks.

KEYWORDS
contagion, diffusion of innovations, inequalities, social networks

1 | INTRODUCTION

As a result of the COVID-19 pandemic, terms like contagion, transmission, and network contacts, are part of common parlance today. Yet, diseases are not the only materials that spread through human interaction. Social scientists have long been interested in the diffusion of innovations—the process by which new ideas, behavior, and practices spread between persons, organizations, and even countries (e.g., Christakis & Fowler, 2007; Fernandez & McAdam, 1988; Granovetter, 1978; Rogers, 2003). Social behaviors, much like diseases, can be "contagious." New ideas and behaviors

can "enter" a locale—find a few early adopters—through a variety of sources such as from a different community, introduction of a new technology, interventions aimed at the cessation of adverse outcomes like smoking, and mass media.

While these bases are important for generating awareness about an innovation, they are rarely sufficient for ensuring widespread community adoption. The ongoing spread of innovations through a community occurs through the medium of social networks—collections of interpersonal or digital relationships interconnecting actors. Connections in social networks can be strong ties, such as close friends and family, or weak ones, such as acquaintances or distant relatives (Granovetter, 1973). At the supra-individual level, ties can similarly take the form of trade relation (e.g., between countries), shared directors (e.g., between companies), and hiring relationships (e.g., between academic departments). Digital networks can also include ties to people an actor has never met, such as influencers on social media.

Social networks facilitate diffusion because ties act as conduits for the flow of information, materials, and influence (Podolny, 2001). Despite availability of information through non-personal channels such as popular media, actors may nevertheless need affirmation from close network ties to adopt an innovation (Chaves, 1996; DiMaggio & Powell, 1983; Soule, 1997; Strang & Meyer, 1993; Strang & Soule, 1998). Ties in social networks can be especially effective in persuading potential adopters who might otherwise be reluctant. The adoption of an innovation sends signals to members of the adopter's networks. These signals can include simple observation (such as use of new technology), discussion of the innovation's virtues (such as benefits of a new exercise program), and conversations about potential adverse outcomes (such as side effects of a new medication).

Ties can also be a source of novel information (such as an impending market crash), which can impel people to pass on that information or alter their behavior in response (e.g., Bond et al., 2012). Behavior, information, and influence can not only spread from a focal person (or ego) to their immediately connected networks members (or alters), but also potentially to their alters' alters. The adoption of a new eating regime by one person may influence the ego's friends to try the new behavior, which, in turn may influence their friends' friends to also attempt it. Influence on connections of connections may not always flow in this indirect way. It is possible for friends of friends to directly observe the ego at some collective setting such as a party. This chain of influence can even go longer to an ego's alters' alters' alters (Burris, 2005; Christakis & Fowler, 2008). Analyzing shared corporate board memberships (or interlocks) in U.S. corporations, Burris, for example, finds that directors who were members of the same company's board were highly likely to make similar political contributions in the 1980 U.S. presidential election. Significantly, he also finds that similarity in contributions extended up to six steps in the chain of shared memberships (A shares a membership with B, who shares one with C, who shares one with D, and so on).

Yet, this process eventually peters out so that behaviors do not generally disseminate endlessly, taking over the entire world. To the contrary, diffusion often occurs in such a way that behavior comes to be "pooled" within groups of densely interconnected persons so that members of such collectives tend to exhibit similar behaviors or possess similar knowledge. Others, who are less connected with or embedded in these groups, are exposed to other influence and, consequently, display different behaviors. This segregated clustering of behavior can have implications for the distribution of resources as well as cultural differentiation (DiMaggio & Garip, 2011; Gondal, 2015; Zhao & Garip, 2021).

More generally, the diffusion of innovations and behavior is a complex process. Its outcomes can range from quick and widespread, sometimes in the face of our best efforts to contain spread (such as COVID-19), to slow and stilted, despite attempts and desires to make adoption pervasive (such as uptake of COVID-19 vaccination among young children in the United States). Which one of these two outcomes obtains, and indeed everything in between these idealized cases, depends on a number of factors, which I discuss below. The balance of this article is divided into three sections. In the first section, I summarize two well-known classical studies of diffusion. In the subsequent section, I discuss three determinants of diffusion—the relationship between social networks and diffusion, characteristics of adopters, and properties of the material being spread. I close with a discussion on some implications of diffusion as well as avenues for future research. I draw on examples and sample literature from diverse disciplines, a reflection of the breadth of the field.

Note that not all the research that I consider here (including the canonical work by Ryan and Gross that I discuss in the next section) relies on the explicit analysis of social network data. In most of these instances, it is not the case that networks are irrelevant to diffusion processes. Instead, based on research that relies on analysis of social networks, literature that does not use such data takes for granted the network-based processes implicated in diffusion outcomes. This is evident from the explanatory frameworks used in this research, where network terminology is often invoked implicitly or heuristically. In some of these cases, collecting network data is not feasible or presents serious difficulties (e.g., Kaufman & Patterson, 2005), while in others, network data are part of the larger project but not used in the analysis shown (e.g., Tavory & Swidler, 2009). On the flip side, some studies I discuss investigate the relationship between social networks and diffusion but pay less attention to analysis of diffusion itself (e.g., Bearman et al., 2004; Tokita et al., 2021). These studies provide important insights into the implications of network structure for diffusion or vice versa. As such, in these and other cases, lack of use of social network data or explicit analysis of diffusion processes should not preclude us from drawing on this literature to make sense of other relevant findings such as processes of cultural change or inequality.

2 | WHAT DIFFUSES THROUGH SOCIAL NETWORKS?

Two classic studies on the diffusion of innovations have been foundational in the field of sociology. Ryan and Gross (1943) analyzed the spread of hybrid corn, which yielded an increased harvest and was more drought-resistant than traditional varieties, in two agricultural communities in Iowa in the 1930s. Nearly all farmers adopted the hybrid seeds in the 13-year period under consideration. Yet, adoption did not occur linearly over time. Instead, their investigation revealed the now well-known "S-shaped" curve associated with diffusion dynamics. Only about 10 percent of farmers adopted the innovation in the first 5 years under investigation, making up the lower flattish arm of the S-shaped curve. Thereafter, the innovation took off, spreading rapidly, giving rise to a steeply upward sloping curve. Finally, the rapid increase leveled off as the remaining "resistant adopters" accepted the innovation, yielding the upper arm of the curve. Ryan and Gross also investigated the role of demographic attributes in adoption outcomes. Finally, while the authors did not expressly investigate the role of social networks in adoption, their pioneering work also highlighted the role of "influencers," such as salesman and neighbors, in spreading awareness about the new variety of corn.

The second study, by Coleman et al. (1957), focused on the diffusion of a new antibiotic "gammanym" (later revealed to be tetracycline), among 85 percent (N = 125) of practicing physicians in four Illinois cities. Unlike Ryan and Gross, these authors formally investigated the role of social networks in diffusion. In addition to information on first use of tetracycline prescriptions, data were gathered on three types of ties between doctors: advice and information, friendship and social connectivity, and case-related discussions. Findings revealed that doctors who were popular in professional networks were early adopters of tetracycline prescriptions. Thereafter, the innovation spread through friendship relationships. The most significant contribution of Coleman, Katz, and Menzel was their demonstration of the role of social networks in mitigating uncertainties associated with the adoption of innovations.

This seminal work on the topic has inspired hundreds of studies in sociology and allied fields such as the diffusion of medical technology (e.g., Holt et al., 2019; Zhang et al., 2015), educational innovations (e.g., Macharia & Pelser, 2014; Mintrom & Vergari, 1998; Noori & Anderson, 2013), public health behaviors and interventions (de la Haye et al., 2019; de Vaan and Stuart, 2019), finance and management strategies (Fiss et al., 2012; Greve et al., 2016; Strang & Soule, 1998), international policy frameworks (Velasco, 2018), social movement activism (Gleditsch & Rivera, 2017; Myers, 2000; Wang & Soule, 2012), and repertoires or ideas (Goldberg & Stein, 2018; Wurpts et al., 2018). Considerable research has also focused on generating and refining theoretical models of diffusion via social networks (e.g., Centola, 2015; Rogers, 2003; Strang & Meyer, 1993; Valente, 1996, 2010). Despite variations in the topics of investigation, there is substantial convergence in the findings produced by this diverse body of work. Diffusion inevitably follows the tell-tale s-shaped curve over time, characteristics of potential adopters are integral, and social networks, howsoever measured, are nearly always implicated in the process.

3 | DETERMINANTS OF DIFFUSION THROUGH SOCIAL NETWORKS

These similarities notwithstanding, innovations and behavior diffuse at different rates and to different degrees. It took over a decade for most of the 259 farmers studied by Ryan and Gross to switch over to hybrid corn. The 125 physicians studied by Coleman Katz and Menzel adopted tetracycline over approximately 15 months. In contrast, the social media app, TikTok, grew from 55 million users in January 2018 to 271 million by December of the same year (CNBC, 2020). The spread of materials or ideas through social networks is shaped by several factors. Chief among these is: (1) the structure of the social networks in which individuals are embedded and through which information spreads, (2) characteristics of potential adopters, and (3) properties of the material being diffused.

3.1 | The structure of social networks

At minimum, diffusion through networks requires connectivity: information or influence can pass from actor i to actor j if they are connected, either directly or through intermediaries. Thereafter, likelihood of spread depends on properties of the network such as average length of pathway connecting nodes, properties of ties such as closeness, and properties of actors such as how influential they are in the network. I discuss feature of social networks and their implications for diffusion processes at three levels: the network, the ties, and the actors.

3.1.1 | Network level

The fragmentation of networks into weakly connected or disconnected components, and the thickness of ties between those components has been shown to be especially significant for the spread of behaviors (Centola & Macy, 2007; Watts & Strogatz, 1998). Social networks are generally understood to be locally "dense" meaning that actors' close alters are also prone to being interconnected to one another (Granovetter, 1973). Localization of density can, nevertheless, produce long distances between nodes, on average, because few nodes have ties that span those dense local spaces. In the context of social networks, distance refers to the number of steps it takes to get from one node to another. Using a chain mail experiment, Stanley Milgram famously argued that most people in the world are six steps apart, on average. This "smallness" of the world hinges on some actors straddling disparate social spaces (e.g., a former CEO in Japan who becomes an academic in the United States) thereby producing bridging ties—pathways connecting two otherwise disconnected or distantly connected parts of a network. By linking or shortening the distance between such spaces, bridges effectively make the world a more connected place, enabling and hastening the spread of behaviors. Indeed, in a highly influential paper, Watts and Strogatz (1998) demonstrate that the injection of bridging ties into networks composed of densely connected local spaces—the construction of "small world" networks—considerably enhances the spread of behaviors. Small-world networks were shown to be implicated in facilitating the rapid spread of COVID-19 (e.g., Schlosser et al., 2020). This research also confirmed the usefulness of lockdowns and travel restrictions for delaying spread by limiting the long-range connectivity characteristic of bridging ties.

The degree of centralization or core-peripheriness of networks as well as the density of connections within the core is also significant for the spread of behaviors and innovations (Assenova, 2018; Bernstein et al., 2022; Nash et al., 2013; Wei & Ming-Sheng, 2013). Generally speaking, networks characterized by high inequality in the distribution of ties have been shown to not only hasten but also heighten the spread of innovations. This is because centralization in networks tends to shorten the average path distance between nodes, making it easier for information to spread. Bearman et al. (2004) articulate two models of diffusion that draw on these properties. While they discuss the spread of disease, the models are general and applicable to the transmission of other kinds of social behaviors. According to the "core" model, a group of densely interconnected actors at the center of a network sustain

infection by circulating it amongst themselves and, then pass it outwards to a less densely connected population. In an "inverse core" model, in contrast, a group of central but internally disconnected persons pass infection outwards to others in the periphery of the network but do not exchange directly amongst themselves. In their own analysis of an adolescent romantic network, Bearman et al. (2004) discover the presence of a "spanning tree"—a chain of interconnections with a central "trunk" and branches that spread outwards from the center. Spanning trees networks lack a core of centrally connected actors. Consequently, the path connecting any two nodes tends to be quite long, which should not only slow down the spread of innovations but also make it easier to implement interventions that prevent or limit the spread of diseases (or other adverse phenomena such as disinformation). Rather than having to locate the most well-connected nodes as in the core models discussed by the authors (see also Valente, 2012), interventions can target almost anyone along the "trunk" of the spanning tree with the goal of stopping further transmission.

3.1.2 | Tie level

Diffusion outcomes are also contingent on the properties of ties interconnecting actors. Most significantly, spread depends on what Granovetter (1973) has influentially described as the strength of network ties. Weak ties, characterized by low emotional intensity and time involvement, can be distinguished from strong ones, such as those with family and close friends. Strong ties tend to be densely connected such that a person's close relations tend to also know one another. The high density of strong ties produces redundancy of information—actors are likely to receive the same information from several of their alters, who have also communicated with one another on account of being interconnected. The implication is that strong ties are unlikely to be carriers of fresh information. Weak ties, in contrast, tend not to be linked directly to each other (my friends from middle school are not likely to know my colleagues at my previous job). This relative "openness" of weak ties allows them to act as bridges connecting disparate parts of social spaces or distinct communities (my middle school friends to my work community) that are otherwise disconnected.

This property grants weak ties the power to play a powerful role in diffusion because, like traveling salespersons, they can carry new information from one social space to another (e.g., Baller & Richardson, 2009; Djelic, 2004; Kreager & Haynie, 2011; Manzo et al., 2018; Rajkumar et al., 2022; Suh et al., 2017; Wurpts et al., 2018). Granovetter (1974) originally applied his theory to investigate the spread of information about job openings. He found that people are much more likely to receive information about employment openings from their acquaintances and distant relations that close, strong ties. Recent research on LinkedIn, a largescale professional online social network, similarly shows that ties characterized by low intensity of interactions and few mutual connections are most successful in creating job mobility (Rajkumar et al., 2022). The study also confirms that strong ties are less effective for the transmission of job-related information. In addition to information, it turns out that weak ties are also important for the transmission of influence. Baller and Richardson (2009), for example, demonstrate that suicidal ideation among adolescents tends to spread through weak ties. Suh et al. (2017), likewise, show that weak ties are instrumental for the spread of smoking among adolescents.

The same structural property that allows weak ties to be successful in transmitting information *between* communities renders them less effective for facilitating diffusion *within* communities (Centola & Macy, 2007; Larson, 2017). Strong ties are much more successful at the latter. This is attributable to both structural and compositional properties of strong ties. Structurally, the redundancy of strong ties is useful for reinforcing the transmission of influence, necessary for the diffusion of culturally non-normative or effortful behavior. An actor may be reluctant to start a new exercise program if she hears about it from an acquaintance, but much more likely if receives multiple positive signals from several of her close friends.

Compositionally, strong ties are effective for the transmission of influence because close relations within social networks are considered to be reliable sources of information (e.g., Lee, 2014; Rutenberg & Watkins, 1997). Lee (2014), for example, finds that prior to the 1973 passage of Roe v. Wade legalizing abortion in the United States,

women seeking to end their pregnancies typically relied on certain types of close relationships (most notably, female friends) for information on how to obtain an abortion. Formal sources of information, such as women's own physicians were sought out far less. Strong ties also serve as "positive" or "negative" role models (Carr, 2012; Lockwood et al., 2005). Positive role models can inspire change whereas negative ones can serve as cautionary tales helping to avoid undesirable outcomes. Finally, network members provide a variety of social support including the kind necessary for sustained behavioral change, especially in addictive behaviors such as smoking (e.g., van Wijk et al., 2019). The effectiveness of strong ties in producing diffusion may also depend on other network compositional factors. In their study of the diffusion of novel pottery techniques in Kenya and India, Manzo et al. (2018), for example, find that weak ties were instrumental in the introduction of techniques to new communities. Further spread within communities hinged on the presence not only of strong ties, but also the involvement of expert users and early adopters in the "teaching" of the technique to uninitiated users. The presence of such users, the authors argue, send the most positive signals, and are considered to be trustworthy sources of information.

Spread also depends upon the degree of homophily of ties—the greater likelihood of people who are similar to one another on attributes, beliefs, circumstances, and values to be interconnected (e.g., Labeyrie et al., 2016; McPherson et al., 2001; Rogers, 2003; Strang & Meyer, 1993; Yavas & Yücel, 2014). Generally speaking, behavioral transmission is more likely to be successful when ties are homophilous (Bras, 2014; Colyvas & Jonsson, 2011; Halberstam & Knight, 2016; Heaton & Gondal, 2023; Koopmans & Vliegenthart, 2011; Rutenberg & Watkins, 1997). While social learning and influence received from close relations is generally viewed as more credible, the process is likely to be even more effective when coming from people with whom one shares attributes, interests, circumstances, subcultures, and habits. People also prefer to compare themselves to others who they perceive to be similar to them and such similarity generates greater confidence in their ability to make changes to their own habits (Erickson, 1988). In support of this, Centola (2011), finds that adoption rates of healthy eating and physical activity in an online community were three times higher in homophilous than non-homophilous networks. Using in-depth interviews, Rutenberg and Watkins (1997) similarly find that women discuss experiences of contraceptive use with other women they know and perceive to be similar to them despite receiving "formal" information about family planning form nurses at clinics.

3.1.3 | Actor level

The relative positioning of actors in social networks also has implications for diffusion outcomes. As argued earlier, networks where some actors are highly popular, but most are not, are effective for the spread of innovations. In addition to the structural implications of centralized networks, as discussed above, success of spread can also be linked to centrality at the actor level. "Core" actors are typically highly influential and can help spread the message quickly by activating their ties. In his review article on network-based interventions, Valente (2012) argues that popular actors are often used as change agents—leaders who champion shifts in habits and behaviors. In their classic study, Coleman et al. (1957), for example, find that popular actors were often first to adopt, passing information onwards to their contacts. Becker (1970) similarly finds that earliest adopters of a readily acceptable health program tended to be opinion leaders. Wang and Soule (2012) show that social movement organizations that are more central in collaboration networks are more likely to send information on protest tactics to other organizations.

Differentiation in popularity has also been shown to facilitate spread in the reverse direction—from peripheral actors toward those in the center (Chen et al., 2021). This is likely to occur when innovations are deemed to be risky or culturally incompatible with existing norms. While conventional health programs spread from the core toward the periphery, Becker also found that health programs that were harder to adopt tended to be accepted first by actors that occupied peripheral positions in networks. Sgourev (2013) comes to similar conclusions about the spread of cubism in early twentieth century Paris. The riskiness of the new paradigm meant that those located at the margins of social networks were more likely to experiment first. Subsequently, fragmentation of the market and uncertainty over evaluation standards aided the spread of the new art form from the periphery to the rest of the network.

The properties discussed thus far rely on direct communication between actors interconnected via ties. Yet, diffusion can also occur without explicit assumption of interaction between indirectly connected "structurally equivalent" actors (White et al., 1976). Two actors are structurally equivalent if they occupy the same structural position in a social network. Two patients being treated by the same doctor, for example, occupy structurally equivalent positions, even if they are not directly tied to each other. Likewise, the two doctors treating the same patient are also structurally equivalent. In a highly influential paper, Burt (1987) distinguishes between cohesion and structural equivalence as bases for the diffusion of innovations. Cohesion facilitates spread for all the reasons discussed above: ties foster communication, trust, and flow of information. The key mechanism undergirding diffusion based on structural equivalence, on the other hand, is competition between actors. Actors occupying the same position in a social network are likely to be shaped by similar forces and are likely to use each other as frames of reference in decision-making.

In re-analyzing Coleman, Katz and Menzel's tetracycline data, Burt concludes that structural equivalence rather than cohesion in physicians' networks was responsible for the spread of the drug—physicians adopted tetracycline because they witnessed their peers also prescribing the same drug, not because their immediately connected advisors and friends also adopted. The implication is that competition likely mattered more than direct discussions regarding the merits of the drug. Others (Harkola & Greve, 1995; Huang et al., 2011; Johnson, 1986) have similarly found structural equivalence to play an important role in diffusion processes. Harkola and Greve (1995), for example, find that diffusion through equivalence is more likely in low-density social networks and cohesion is more effective in networks with higher density. Note that structural equivalence as the basis for diffusion does not undermine the role of social networks in generating spread. Rather, it attributes causality to positionality in place of communication in interaction.

3.2 | Characteristics of potential adopters

In addition to their position in networks, the disposition and ability of actors to change or adopt new behaviors and habits to which they are exposed through their networks, also depends on attributes such as age and gender as well as structural constraints that shape access (e.g., Bearman & Moody, 2004; Manzo et al., 2018; Soule, 1997; Valente, 2010; Valente et al., 1997). Generally, actors with higher social status and those that occupy positions of influence in social networks are more likely to adopt innovations and do so sooner than others (Wejnert, 2002). Examining family planning strategies within social networks, Valente et al. (1997), for example, demonstrate that younger, wealthier, and more educated women are more likely to use contraceptives. On the other hand, as discussed above, highly risky innovations are sometimes more likely to adopted by actors that are marginal in the network.

Attributes are also important at supra-individual levels. Investigating the largescale diffusion of legislation and creation of charter schools in the United States, Renzulli and Roscigno (2005) show states with strong teachers' unions were less likely to adopt legislation in favor of charter schools. Nix et al. (2020), likewise, demonstrate that U.S. police agencies' adoption of body-worn cameras depended critically on attributes of the agency including size, region, and demographic composition of communities served. Generally, these findings imply that, despite similar levels of exposure within networks, some actors may be more susceptible or able to commit to behavioral change.

In addition to shaping likelihood of adoption, individual attributes also have implication for *when* actors adopt innovations. Rogers (2003) distinguishes between five adopter categories: innovators, early adopters, early majority, late majority, and laggards. Innovators are not afraid of experimenting, are better off, and tend to have widespread and more cosmopolitan networks. Early adopters rely on information supplied by innovators and tend to be opinion leaders in their communities. Burt (1987), for example, shows that, within physician networks, early adopters of tetracycline were younger and more likely to keep abreast of medical and scientific developments. Early and late majorities lie on either side of the mean adoption period. The former tends to interact considerably with their peers and make deliberate decisions about adoption. The latter are typically less well-off and adopt due to economic necessity and peer pressure. Finally, laggards are generally the most conservative, and often occupy peripheral positions

in networks. Analyzing the cross-national spread of laws granting family rights to lesbian and gay families, Dotti Sani and Quaranta (2022) find that individual-level attitudes toward homosexuality remained largely unchanged over the last two decades in "laggard" countries that have been slowest to introduce legislative change.

These varied dispositions toward adoption can be formalized in terms of adoption "thresholds," which refers to the number or proportion of a community that needs to adopt before the target individual adopts an innovation (Granovetter, 1978; Schelling, 1978). A threshold of zero implies that an actor is open to adopting an innovation even if no one else has adopted. A threshold of "one," likewise, implies that exposure to a single "infected" actor is adequate to convince a potential adopter. Early adopters tend to have low thresholds of adoption—the innovators in Rogers' terminology. Laggards, in contrast, are conservative, and need a significant proportion to have adopted before they make a decision. Variability in the distribution of thresholds over agents in a population are associated with the s-shaped curve of diffusion. Typically, a small fraction of actors has low thresholds producing the first flat segment of the curve. This early phase produces a "critical mass" of adopters in the community thereby convincing a larger fraction with middling thresholds, which, in turn, induces large-scale adoption (Granovetter, 1978; Granovetter & Soong, 1983; Schelling, 1978). This stage produces the steep upwardly sloped section of the s-curve. Finally, a small fraction of the potential adopters has high thresholds. As most actors have already adopted by this time, the slope softens again to yield the top branch of the "S."

3.3 | Characteristics of the material being diffused

Adoption thresholds have also been linked to types of innovations. Some information is readily believable and easy to pass on, such as natural disaster alerts. Others are especially memorable because of their minimally counterintuitive character, such as rumors, and thereby lend themselves to rapid spread (Greve et al., 2016; Noymer, 2001). In these cases, receiving signals from one or a few sources may be sufficient for adoption. The diffusion of such materials is consequently considered to have low thresholds for adoption. Weak ties are efficacious for the spread of such innovations. This is because weak ties, often the sole bridge interconnecting distant social spaces, can successfully carry information between locations. If multiple sources of influence were necessary, weak ties, while able to carry information from one space to another, would not be able to convince actors on the other side of the bridge to adopt.

Other types of innovations, in contrast, are sufficiently removed from cultural scripts that significant influence and convincing is necessary for their adoption (e.g., Centola et al., 2005; DiMaggio & Garip, 2011; Gibbons, 2004; Hedström, 1994; Liu et al., 2010; Wejnert, 2002). Affirmation and interpretive work may also be necessary when innovations require considerable expenditure of resources or other forms of effort. The adoption of these types of behaviors or innovations are contingent upon receipt of influence from multiple reliable network partners. As distinct from low thresholds of adoption (so-called simple contagions), the spread of such materials has been termed "complex" contagion (Centola, 2011; Centola & Macy, 2007).

While low threshold behaviors can be spread through weak ties, Centola and his colleagues argue that network structures conducive to the transmission of complexly contagious behavior relies on locally dense ties that are rich in bridges. Multiple local bridges occur if several actors jointly straddle two or more local network neighborhoods. The redundancy of multiple bridges is a "waste" in simple contagions because additional bridges carry no new information. This same redundancy, however, is necessary when behavioral transmission is dependent on multiple reinforcing signals. Imagine, for example, a couple composed of actors, A and B, who adopt an innovation from jointly interacting with another couple. If the threshold for transmission is at least two, neither half of the couple can transmit the idea alone (say to their distinctive friendship or occupational networks). Yet, together, they can transmit to other networks to which they jointly belong. Spread of several types of innovations and behaviors including information in digital spaces, online memes, health behaviors, and political ideology have been shown to spread through complexly contagious processes (Centola, 2011; Monsted et al., 2017; Sprague & House, 2017; Youngblood, 2020).

Finally, Rogers (2003) elaborates on five properties of the innovation and their effect on rates of adoption. (1) The higher the "relative advantage" of an innovation, the more benefits it provides relative to preexisting substitutes;

(2) complexity refers to the understandability of an innovation; (3) trialability refers to the degree to which an innovation can be tried-and-tested prior to complete adoption; and (4) innovations that can be observed with relative ease have high observability. Generally speaking, innovations with high relative advantage, low complexity, high trialability, and high observability are likely to diffuse more widely and quickly.

The fifth property—compatibility—pertains to the consistency of an innovation with existing cultural scripts and prior experiences. Innovations that are not compatible with prevalent norms, values, and practices are unlikely to diffuse successfully (see also, Strang & Soule, 1998). Tavory and Swidler (2009), for example, elaborate on the cultural connotations associated with condom use in rural Malawi. In place of a binary between safe versus risky health practice, cultural meanings of condom usage as indicative of casual sex places serious barriers on widespread use. On the flip side, Abrutyn et al. (2020), argue that exposure to suicide attributes greater imaginability to the act for youths because they witness someone "like them" using it as a means for escape.

4 | IMPLICATIONS OF DIFFUSION THROUGH SOCIAL NETWORKS: HOMOGENIZATION, INEQUALITY, EVOLUTION, AND INTERVENTIONS

The most straightforward consequence of the diffusion of innovations through social networks is that it produces changes in behaviors such as adoption of new technologies and development of new habits. At the same time, variability on the properties described above mean that innovations diffuse at varying degrees and rates across groups. This divergence can, on the one hand, lead to the maintenance and consolidation of similarity within groups (DiMaggio & Powell, 1983), and, on the other, produce and exacerbate inequalities and differentiation across groups (e.g., DiMaggio & Garip, 2011; Gondal, 2015).

Drawing on the work of John Meyer, DiMaggio and Powell (1983) argue that diffusions that have spread sufficiently acquire a high degree of legitimacy. This social acceptability increases the likelihood of adoption regardless of its value to an organization. This process produces a high degree of homogenization across organizations occupying the same field. In the context of the United States, for example, rhetoric focused on "diversity," used to showcase commitment to inclusiveness and appreciation of racial differences, spread rapidly within higher educational institutions and corporations during the last few decades of the twentieth century (Berrey, 2011; Dobbin, 2009; Posselt, 2016). This institutionalization of diversity-related discourse created conditions for university administrations to increasingly come under pressure to release public statements in response to instances of racial injustice within their communities. The practice became especially salient in the aftermath of the murder of George Floyd on 25 May 2020. In the summer that followed, hundreds of higher educational institutions and corporations released statements in declaration of their positions (Knoph et al., 2021; Meikle & Morris, 2022; Stack, 2021). Research investigating these statements shows considerable similarity in the rhetoric used in these documents including themes focused on "justice," "equity," and "inclusiveness." Likewise, organizations also make comparable commitments to the creation of policy and spaces that facilitate equity and inclusion. Consistent with DiMaggio and Powell, these studies illuminate how pressures toward adoption of ideas and practices in a field can produce a remarkable degree of organizational conformity.

Widespread adoption in some groups but not others, on the other hand, can contribute to the production and exacerbation of cultural difference and inequality. As discussed above, economically and socially advantaged persons face fewer barriers in adopting innovations. Consequently, they are more likely to adopt innovations earlier than others. Nevertheless, ongoing spread, especially of innovations that rely on interpretive work, occurs through social networks. And ties in such networks generally tend to be homophilous on numerous attributes including socioeconomic status. It turns out that under conditions of status-based homophily, the heightened presence of initial adopters in networks of advantaged actors is sufficient to ensure that innovations spread at faster speeds and to greater extents among elite groups (Gondal, 2015). Although these divergences can narrow in some cases, they may persist indefinitely in others, leading to "differential diffusion" (DiMaggio & Garip, 2011). This process can exacerbate inequalities in two ways.

First, innovations that are conducive to the improvement of life chances, such as positive health interventions or new technologies, can spread unevenly, producing biases in the distribution of benefits offered by them (Ferrence, 1989; Pampel, 2002; Stern et al., 2009). Inequality in access to the Internet in the United States by race, educational attainment, and income have narrowed since the nineties but persist even today (DiMaggio et al., 2004; Dolcini et al., 2021). In a different context, Labeyrie et al. (2016) demonstrate that homophily on location of residence and ethnolinguistic groups positively influences exchange of sorghum seeds in Kenya. At the same time, social barriers to exchange linked to kinship norms limit exchange of seeds producing diversity in crop patterns.

Second, widespread adoption of innovations in some groups but not others can contribute to the reproduction of symbolic distinctions between groups. Any innovation may originally carry a given cultural connotation (say, focused on its use value). Yet, once it becomes widespread in some socially ordered groups but not others, it can become integrated into the existing system of meanings associated with those hierarchies. This new layer of meaning can contribute to maintaining and exacerbating existing inequalities (Bourdieu, 1984; Lamont & Molnár, 2002). Differential diffusion of ideas and tastes, for example, is consistent with this process (Gondal, 2018; Kaufman & Patterson, 2005; Morgan et al., 2018). Using survey data from 15 European nations, Pampel (2002), for example, argues that smoking is more prevalent among low status groups because the elite are both more aware of the adverse health effects of smoking and because the practice is symbolically associated with low-status groups.

The diffusion of innovations can also have implications for the evolution of social networks. Although it is typical and analytically more tractable to think of social networks as the "pipes" through which innovations and other stuff flows (Podolny, 2001), networks can also change in the process of diffusion. On the one hand, network evolution can be incidental to the process of diffusion. This occurs, for example, if ties dissolve or form for reasons that are unrelated to the spread of materials through networks. But social networks can also change as a result of the diffusion process. Tokita et al. (2021), for example, show that Twitter users who followed highly polarized news outlets tended to lose ties to those with competing political ideologies leading to the creation of politically homogenous social networks, and potentially stemming the flow of information across political lines.

Complementary to the evolution of networks, research also shows that meanings associated with innovations also tend to change during the process of diffusion (Fiss & Hirsch, 2005; Kaufman & Patterson, 2005; Levitt & Merry, 2009). Kaufman and Patterson, for example, demonstrate that meaning and cultural significance associated with the sport of Cricket evolved considerably as it spread from England to other nations, especially its colonies. A formerly rural sport, it came to be associated with the aristocratic classes in England. In the colonies, it was used as a tool for maintaining hierarchical distinctions and as an "agent of civilization." Today, in contrast, its former colonies, especially India, are arguably cricket powerhouses where the sport transcends economic and social hierarchies.

Research on the uptake and spread of innovations also has implications for health-based interventions aimed at the prevention, cessation, or moderation of unhealthy behaviors. Targeting individuals for behavioral modifications may not be effective if their close personal ties such as friends and family are sources of counteracting influence. The innovation (here, intervention) will likely fail to be adopted by the target individual. Khubchandani et al. (2021), for example, find that individuals were much more likely to refuse COVID-19 vaccines if they did not have a friend or family members who was hospitalized or died of the disease. Onnela et al. (2016), likewise, find that polio vaccine hesitancy in Malegaon, India tends to be clustered within social networks such that households resisting vaccinations tend to be in conversation with others that share their views on immunization. The implication is that interventions targeting groups of interconnected persons, rather than single individuals, may be more successful in producing sustained behavioral change (Alexander et al., 2022; Centola, 2018; Heaton & Gondal, 2023; Maman et al., 2020; Valente, 2012). In support of this thesis, Christakis and Fowler (2008), for example, find not only that smoking among adults tends to be clustered within networks but also that cessation tends to follow a similar pattern—groups of interconnected people are likely to quit smoking together. Alexander et al. (2022) similarly find that interventions aimed at connected friends were more effective in the uptake of iodized salt than interventions targeted at individuals.

A further complicating factor is that because health-based interventions, such as those aimed at smoking cessation, can have varied success, they can generate feelings of pessimism leading to abandonment of the intervention

(e.g., Baxter et al., 2010). Strang and Macy (2001) identify conditions under which innovations that are initially adopted are subsequently rejected. This is likely to occur not only when innovations are ineffective, but also when they are only modestly effective in improving outcomes. Actors are likely to become dissatisfied with such changes leading to rejection and search for better solutions. Stability in adoption is more likely when innovations are highly effective in improving outcomes. The implication is that health-based interventions with low success rates are more likely to fail as stakeholders search for more successful alternatives. In such cases, interpretive work from trusted alters and community experts can be effective (e.g., Manzo et al., 2018; Rutenberg & Watkins, 1997; Sarkar et al., 2019).

Valente (2002) argues that providers, who attempt to persuade clients to change their behaviors in clinical settings, and outreach workers, who go door-to-door to make contact with clients in their own homes are especially effective in inducing behavioral change. These programs are successful because information is received from agents perceived to be knowledgeable and trustworthy. One way to supplement these approaches is to shift the focus from targeting individuals to networks of affected persons. Centola (2018), for example, finds that clustering seeds within network neighborhoods was more successful in a health intervention than randomly scattering seeds across the network space because randomly scattered seeds faced opposing pressures from connected network members.

The targets of health-based interventions are often disadvantaged communities, such as those living in public housing developments in the United States, because they face disproportionately high burdens of chronic disease (e.g., Chang & Lauderdale, 2009; Digenis-Bury et al., 2008; Phelan et al., 2010). Deploying our knowledge not only of how social networks matter for transmission and adoption but also the implications of diffusion for the reproduction of inequalities is especially important in such interventional contexts. In their analysis of smoking cessation, Christakis and Fowler (2008) also find that more educated subjects were at higher risk for quitting smoking if their network members also quit. Moreno-Moldenaodo et al. (2018) similarly find that school-based nutritional interventions were more successful for children whose parents were more educated and materially better off. Moreover, eating behavior was also found to cluster within peer networks so that nutritional improvements were more likely for a child if their friends also adopted similar habits. The implication is that interventions need to be designed in a way that accounts for the distribution of demographic attributes as well as the structure and composition of local social networks.

Although work on the diffusion of innovations through social networks has progressed considerably, ongoing research is continuing to advance the field in critical ways. First, research that contributes to the enhancement of theoretical models of diffusion as well as its implications for the types of outcomes discussed above continues to fill persistent gaps in the field (e.g., Assenova, 2018; Deffuant et al., 2005; Gondal, 2015; Moody et al., 2017; Yavas & Yücel, 2014; Zhao & Garip, 2021). While the implications of network centralization and density on diffusion are known, for example, Assenova's (2018) work contributes to the literature by investigating interactions between the two variables. Research drawing on such simulation-based techniques has been especially important for predictions and interventions associated with COVID-19 (e.g., Page et al., 2022; Prieto & Ramírez, 2021; Thomas et al., 2020). Another growing area of research involves leveraging online data for exploring diffusion on a massive scale (e.g., Chen et al., 2021; Felmlee et al., 2020; Rajkumar et al., 2022). Online platforms are also useful in contexts where in-person data are missing or infeasible. Theoretical research establishes, for example, that homophilous networks are conducive to the spread of innovations (Gondal, 2015; Rogers, 2003). Yet, research investigating the effects of homophily on health interventions in offline spaces is lacking (Heaton & Gondal, 2023). In such contexts, research using online platforms has shown the positive effects of interventions in the context of homophilous networks (Centola, 2011).

Finally, the use of novel methodologies such as Exponential Random Graph Models (ERGM) and Stochastic Actor-Oriented Methodologies (SAOM) as well as the simultaneous use of empirical data modeling and simulations to investigate outcomes and determinants of diffusion is on the rise (e.g., adams & Schaefer, 2016; An & VanderWeele, 2022; Becker et al., 2020; Elkink & Grund, 2022). adams and Schaefer, for example, combine empirical data on high school friendship networks with simulation models to show that seemingly identical interventions can have widely varying effects on adolescent smoking outcomes depending on initial smoking prevalence and popularity of smokers. The statistical modeling of empirical data and use of estimates as inputs in simulation models or use of

simulations as tools to evaluate plausibility of empirical findings contributes to improving our understanding of diffusion processes as well as its implications.

To conclude, literature in the diffusion of innovations through social networks has come a long way since Ryan and Gross's early work in the field. We know today not only that social networks matter for the diffusion of innovations but also how the structure and composition of networks are critical to the process. In addition to refining theoretical models, drawing on lessons from the spread of COVID-19, which laid bare the potentially devastating consequences for vulnerable populations, ongoing discourse in the field should also focus on inequality in the diffusion of materials.

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