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A Multidisciplinary Understanding of Polarization

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This article aims to describe the last 10 years of the collaborative scientific endeavors on polarization in particular and collective problem-solving in general by our multidisciplinary research team. We describe the team's disciplinary composition—social psychology, political science, social philosophy/epistemology, and complex systems science—highlighting the shared and unique skill sets of our group members and how each discipline contributes to studying polarization and collective problem-solving. With an eye to the literature on team dynamics, we describe team logistics and processes that we believe make our multidisciplinary team persistent and productive. We emphasize challenges and difficulties caused by disciplinary differences in terms of terminology, units/levels of analysis, methodology, and theoretical assumptions. We then explain how work disambiguating the concepts of polarization and developing an integrative theoretical and methodological framework with complex systems perspectives has helped us overcome these challenges. We summarize the major findings that our research has produced over the past decade, and describe our current research and future directions. Last, we discuss lessons we have learned, including difficulties in a "three models" project and how we addressed them, with suggestions for effective multidisciplinary team research.

Keywords: multidisciplinary research team, polarization, collective problem-solving

Polarization is often viewed as one of society's greatest ills. Polarization leads to the impediment of communications between disagreeing groups, the increase of disagreement about facts and interpretations of those facts, the blurring of the line between facts and opinions, the proliferation of false information within each group, the distrust between opposing groups, the emergence of radical groups, and the failure to reach a nationwide consensus on important issues, from welfare programs to national security (Fishkin, 2009; Kavanagh & Rich, 2018; Sunstein, 2002;

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Jiin Jung

Vallacher, 2015). What causes polarization? How do groups become radicalized? When do groups reach a consensus? Can a polarized society be depolarized and integrated? What can bring segregated groups together again? Does polarization always have negative consequences in group functioning?

Over the past decades, different disciplines have advanced our understanding of polarization remarkably. In social psychology, group polarization is defined as "the tendency for group discussion to produce a group decision or consensual group position that is more extreme than the mean of individual group members' prediscussion attitudes and opinions in the direction already favored by the group" (Isenberg, 1986, p. 1141, see Hogg, Turner, & Davidson, 1990, for an integrative perspective). It is measured by how much the average attitude of group members has changed after group discussion. Different underlying mechanisms of polarization have been documented in different subfields of social psychology. For example, polarization can occur because group members conform to a polarized ingroup norm, as in social identity theory (Abrams, Wetherell, Cochrane, Hogg, & Turner, 1990). Small group research has shown that one cause of polarization is that information that supports the majority opinion is more likely to be shared (Larson, 1997; Levine & Tindale, 2015; Martin & Hewstone, 2008). The attitude change and social influence literature focuses on how people tend to selectively search for confirming information (Lord, Ross, & Lepper, 1979). In the social cognition field, researchers have demonstrated that merely thinking about an attitude object makes the attitude more extreme and certain (Clarkson, Tormala, & Leon, 2011; Tesser, 1978).

Political scientists have studied the phenomenon of polarization for decades now, most notably comparing popular versus elite polarization (Hetherington, 2001) and political versus cultural polarization (Hetherington, 2009). In Fiorina and Abrams' review on the subject, they noted that "most scholars hold an intuitive notion of polarization as a bimodal distribution of observations" (Fiorina & Abrams, 2008, p. 566). Although bimodality is the signature marker of polarization, other more practical measures for polarization have been carefully deployed such as the spread of attitudes on an issue (DiMaggio, Evans, & Bryson, 1996), the homogeneity or issue coherence of distinct groups (Baldassarri & Gelman, 2008), and the kurtosis of the distribution (i.e., the extremity of observations within a distribution) of beliefs, attitudes, or policy proposals (Kinder & Kalmoe, 2017). Different kinds of polarization emerge for distinctive reasons, but outbidding—where parties have an incentive to take extreme positions to cater to their party base—along with media pressures and endogenous lawmaking resulting in practices like gerrymandering, all produce dynamics consonant with the outcomes we observe. Political scientists have also noted the cultural determinants of polarization as well, where, as Hetherington and Weiler (2018) pointed out, Democrats are the party of the Prius while Republicans are the party of the pickup truck. The presence (Layman & Green, 2006) and absence (Mason, 2018) of cultural faultlines and cross-cutting cleavages can explain how political polarization has bled into our cultural lives as well.

Polarization has been addressed within social epistemology through the problem of peer disagreement. Epistemic peers—people who have equally good perceptual and reasoning abilities—may form conflicting beliefs, yet cannot both be correct. Epistemologists have been debating over whether and how much belief-revision is rational once peer disagreement is recognized and peers have had a full chance to share the support for their respective views. Some argue that a rational response to disagreement is to reduce confidence in one's beliefs (Feldman, 2007), whereas others argue that it can be rational to maintain one's prior beliefs (Kelly, 2010). The latter causes polarization (Kelly, 2008).

Finally, in complex systems science, social systems are understood as complex adaptive systems that are composed of many parts interacting with one another at different levels (Miller & Page, 2007). Polarization is a system property that emerges from multiple complex interactions among agents over a period of time. Segregation emerges when agents migrate to neighborhoods where they can be surrounded by similar agents in terms of ideology, socioeconomic status, or race and ethnicity (Schelling, 1971). Polarized groups, in which group members' opinions are internally homogenous but differ starkly between groups, emerge in a large society when people are influenced by similar others (Axelrod, 1997).

Patrick Grim

Building on this mature literature, our multidisciplinary research team integrated theories and methods from these four disciplines—social psychology, political science, social philosophy/epistemology, and complex systems science—to investigate polarization. Studying polarization requires in-depth investigation on collective problem-solving and decision-making as well as social influence and group dynamics. In this article, we describe the last 10 years of collaborative scientific endeavors by our multidisciplinary research team. First, we highlight how our team composition helps us better understand polarization. Second, team dynamics and logistics are described. Third, we address challenges and difficulties caused by disciplinary differences in terms of terminology, units/levels of analysis, methodology, and theoretical assumptions and describe how we developed an integrative framework to resolve the challenges. We explain complex systems science and agent-based modeling as primary methods to integrate theoretically and methodologically different disciplinary theories of polarization. Fourth, we highlight some key contributions that our team research has produced over the past decade, and describe our current research and future direction. Last, we discuss lessons we learned from our collaborative work and offer suggestions for effective multidisciplinary team research.

Multidisciplinary Team Composition

Social phenomena can hardly be well understood at a single level of analysis. Social systems are complex, with multiple levels from individuals through small groups to large societies. Many factors at different levels interact to influence one another and different disciplines focus on different levels of analysis. To have a fuller understanding of polarization, our team is composed of the scholars of four different disciplines that are complementary to one another.

Unique Knowledge, Skills, and Approaches

Social psychology employs experiments, an excellent method to verify causal relations with high internal validity. It seeks to explain polarization primarily at intraindividual, interpersonal, and small group levels, such as majority and minority influence (Crano, 2010; Levine & Tindale, 2015; Moscovici, 1976), social identity and self-categorization (Tajfel & Turner, 1986; Turner, Hogg, Oakes, Reicher, & Wetherell, 1987; also see Abrams & Hogg, 2010), social learning and reinforcement (Bandura, 1977; Skinner, 1938), and group problem-solving processes (Stasser & Titus, 1985).

Political science provides an understanding of polarization at both meso- and macrolevels. It focuses on the roles of social structures and institutions in consensus formation and opinion polarization, such as voting mechanisms, deliberation, hierarchy in representative democracy (Anderson, 2006; Marquis de Condorcet 1785/1995; Landemore & Page, 2015), and political institutions and media (Iyengar & Hahn, 2009).

Social philosophy/epistemology studies the social dimensions of knowledge—how knowledge and beliefs form, are contested, consensually validated, and disseminate in epistemic communities via social interactions and communications. It addresses questions regarding whether epistemic communities can reach truth via rational argumentation and debate (and if so, how). The aims of social psychology and political science are descriptive—attempts to describe how things are. The aims of social epistemology are normative—attempts to determine what is rational and what shape the search for knowledge should take.

Finally, complex systems science offers an excellent integrative theoretical framework and research method that can establish links from microlevel foundations to macrolevel phenomena, and their cross-level interactions (Epstein, 2007). The integrative approach makes it possible to test the combinatory effects of multiple interacting factors at different levels of analysis, to track trajectories of those effects across time, and to measure macrolevel emergent consequences.

Shared Skill Sets

Multidisciplinary work can be facilitated by the creation of "boundary objects" (i.e., artifacts that serve as a common ground for differing perspectives). Boundary objects serve to integrate distinct conceptual approaches into a single shared framework that the group can use to mediate com-

Daniel J. Singer

munication across disciplinary boundaries (Pennington, 2010). Indeed, upon reflection we suspect that one key to our group's success is a shared commitment to agent-based modeling. While agent-based modeling is not inherently multidisciplinary, given that we had a multidisciplinary group, we think that having a shared methodology facilitated communication and obviated a number of issues that have been reported to cause problems (O'Rourke & Crowley, 2013). While each member of the group is "conversational" in modeling, some team members (Bramson, Grim, and Singer) are truly experts in the construction of computation models and typically take the lead in the building phase. In contrast, more empirically oriented members (Berger, Jung, Kovaka, and Holman) bring the models in contact with the empirical literatures in their respective disciplines. Yet this crude partition obscures the fact that every member connects the models with work in their discipline.

Given a common language, our breadth of expertise allows the group to survey a wide scope of literatures that speak to the same conceptual terrain, but that often remain siloed in their respective disciplines. Although we can identify a political scientist (William Berger), a social psychologist (Jiin Jung), epistemologists (Patrick Grim, Daniel J. Singer, Bennett Holman, and Karen Kovaka), and a complex systems scientist (Aaron Bramson) in our team, no researcher can be defined by a single discipline. All have multidisciplinary backgrounds. The knowledge background of our team members encompasses a wide, diverse range of disciplines—biology, cognitive science, complex systems science, developmental and clinical psychology, epistemology, geosciences, mathematics, social psychology, political science, philosophy, and statistics. As we have built up our understanding of polarization and collective problem-solving, members have been interested in understanding what aspects of the phenomena are grasped in alternative conceptualizations.

Team Dynamics and Logistics

Many multidisciplinary teams form, but they often fade away. In this section, we describe team logistics and processes that we think have made our team productive and persistent, integrating our reflections into the existent literature on the science of team science and innovation (for reviews, see Hall et al., 2018; Thayer, Petruzzelli, & McClurg, 2018).

Weekly Research Meetings and Information Sharing

Suh and Shin (2010) have found that, particularly for geographically dispersed research teams, regular meetings are crucial to maintaining continuing participation. Our group has been meeting almost every week for nine years and we believe these weekly meetings have been critical to the team's persistent productivity. Though we are now quite dispersed, as with many other successful collaborations, our group began at a single institution (Freeman, Ganguli, & Murciano-Goroff, 2014)—The Center for the Study of Complex Systems at the University of Michigan. Accordingly, our initial research meetings were face-to-face, but as many team members moved to other states or countries, we began video conferencing. While we generally meet around 10 a.m. (Eastern Standard Time) later in the week, we renegotiate the meeting time every semester. One of the remarkable aspects of the group is its continuity given its members being located in anywhere from three to five time zones at a given time. (The most radical case was one summer in which members were in Seoul, South Korea; Ghent, Belgium; Anchorage, Alaska; Claremont, California; Ann Arbor, Michigan; and Philadelphia, Pennsylvania). Dedication and flexibility are often required. Research agendas are provided via e-mail a couple days before each meeting. After the meeting, agendas are summarized and shared via e-mail. We use Dropbox to share research-related information (literature, models, data, etc.). We believe these technologies help our team function efficiently.

Open Mindset, Trust, and Skepticism

Multidisciplinary communication can be difficult due to disciplinary differences in constructs, assumptions, and research cultures. However, these issues have not been particularly problematic in our team. One possible explanation is that we have created an environment that promotes team psychological safety (Edmondson, 1999). Crowston, Specht,

Aaron Bramson

Hoover, Chudoba, and Watson-Manheim (2015) have found that open-minded environments in which individuals could develop trust, promoted innovative outcomes. We approach our interactions with a very open mindset that (tries to) hear critical feedback as helpful. However, unlike the supportive and receptive communication identified by Crowston et al. (2015), many of our discussions are driven by skepticism: someone proposes an idea and others try to shoot it down. This is a tough way to interact with people, especially if you do not know their intention and trust that they ultimately are trying to be helpful. It might also be worth noting that this might make our group interactions seem somewhat hostile to an outsider. Accordingly, efforts are made to explain the value of this approach to new members: we have found by experience that the ideas and arguments that can withstand our own skepticism are much more likely to hold up to peer review and, we hope, simply be better-formed ideas and arguments.

First Draft Writing

Each project has a lead author who is in charge of coordinating work on the paper. Generally, very early on in the project the lead writes a first draft of the paper and shares it with other members. While much of this draft may ultimately be discarded or replaced, we think it is usually the initial brainstorming phase when a project fails to move forward because people have too many different thoughts about how a particular topic might be developed. Having a lead on the project write up a first draft clarifies its focus, and the team can move onto the execution phase.

Project Development and Task Divisions

We do not have members who dictate topics and research technique. When we are ready for a new project, we hold a series of brainstorming sessions. If a consensus finds a proposal interesting, the team starts working on the project. Proposals generally fall in the domain of collective problem-solving and decision making, collective knowledge formation and change, and polarization.

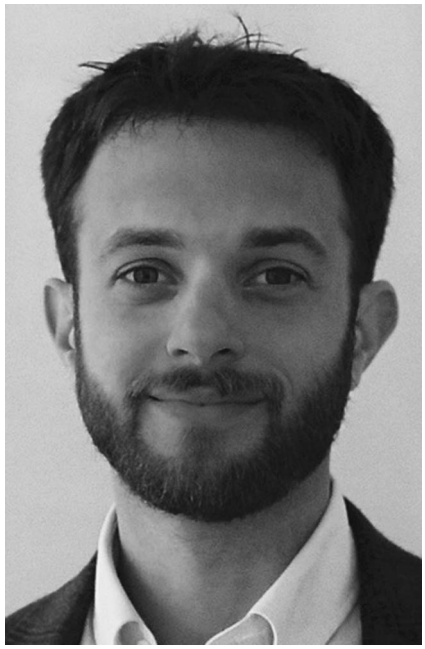
Cummings and Kiesler (2007) found that creating subgroups to work on different aspects of a project was crucial, especially for multiuniversity teams. We have found this to be true, so long as the project also has a lead (see the "three models" section below for a description of the problems that arose with a less hierarchical structure). Typically, the lead is the person who proposed the project. The leader is in charge of writing drafts, leading debates on the topic during research meetings, and handling journal submissions. During the project, the leader is also in charge of identifying what needs to be done, but group members volunteer for what tasks they are willing to take on. This is typically sufficient to keep projects moving. This transition from the open-ended and egalitarian brainstorming phase of projects to the more leader-driven main phase of the project may well be a good example of how our group has learned to manage the conflicting demands of innovation and implementation (Thayer et al., 2018).

After a decade of collaboration, team members are well aware of each other's expertise and skill sets. Based on this well-developed transactive memory (Wegner, 1986, 1995), our team members organically take on tasks that suit their expertise. The development of such collective familiarity is a benefit of long-running teams that has been shown to increase group effectiveness (Mathieu, Maynard, Rapp, & Gilson, 2008).

Occasionally, individual members have been seen to be failing to pull their weight, but these incidences are dealt with directly and respectfully by the group leader contacting the individual, explaining the situation, and confirming that the member is still committed to participating in the group. Depending on their priorities, members can recommit to contributing to the group or choose not to be part of future projects. Our policy on credit sharing goes a long way to inspire group commitment and group cohesiveness.

Credit Sharing

Collaborative problem-solving can be promoted by ensuring that rewards accrue to the team rather than specific individuals (Kramer, Thayer, & Salas, 2013). We think it has been important for our group operation that credit was always spread around, and always shared. The understanding was that everyone operative in a project would appear as an author, with order by consensus on contribution level. Potentially disruptive would be any perception that some-



William J. Berger

one was taking individual credit for work developed collaboratively. Individuals have always been encouraged to present group work with the understanding that prominent credit would be given to all participants in the group work on which it was built. Group norms are sufficiently flexible that members are allowed and even encouraged to publish follow-up papers, with or without collective attribution. While credit does in some sense lead every group member to pitch in their time, the overriding lack of egotism in the group is a cornerstone of its harmony and success, allowing for individuals to pursue their own work, even when grounded in that of the group.

Casual Research Environment

The amount of pressure that a group is under is a contextual factor that moderates group dynamics (Salas, Shuffler, Thayer, Bedwell, & Lazzara, 2015). In this regard, our collaboration is a low-stakes environment, because each member has independent projects that are primary to their research agenda. None of us is solely dependent on the success of the group. Team projects can inspire our independent projects and vice versa. While Van Mierlo and Kleingeld (2010) find that high-stakes environments lead to higher degrees of risk taking, we find that this low-stakes research environment allows us to be flexible and to pursue research topics that we genuinely think important and interesting.

A Sense of Academic Freedom

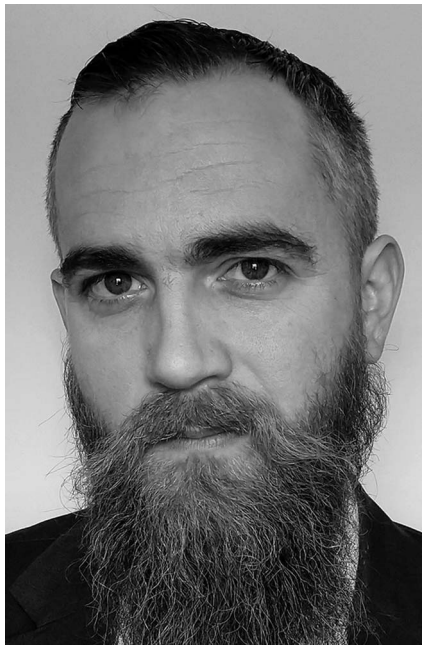
Lastly, we think our collaboration provides us a sense of academic freedom. Disciplines usually have their own way of viewing, interpreting, and analyzing the world and problems within it. Compartmentalized scientific communities can facilitate clear communication and intensely focused research, but can limit the breadth of research. Collaboration is an opportunity for us to be able to learn new knowledge developed by other disciplines, incorporate it with knowledge we are familiar with, and conduct research that cannot be easily done within-discipline. We believe this sense of academic freedom makes us genuinely enjoy the team research, and it motivates us to continue this collaborative endeavor. Beyond this freedom, however, the group fosters a collegial climate of genuine curiosity. Members are friendly with one another (often teasing each other on calls) and strongly motivated by intellectual playfulness. This curiosity is the bedrock of the group's mode of operation. Valuing the strengths of other disciplines and openness to explore new topics outside members' respective areas of expertise have been shown to facilitate multidisciplinary work (Vogel et al., 2014) and it is both why many of us were drawn to the group and one reason we think that we have been successful.

Overcoming the Challenges of Conceptual Ambiguity

Disambiguation of Polarization Concepts

Numerous writers on multidisciplinary work have noted that conflicting uses of central terminology can cause difficulty (O'Rourke & Crowley, 2013; Vogel et al., 2014). Our team found that this problem could be transformed into an important project in its own right. In the process of reviewing the literature for our own model of social polarization, we were immediately struck by the variety of conceptual, terminological, and mathematical differences among authors in simply defining polarization. In some cases, multiple concepts were invoked within a single paper without differentiation. In some cases, polarization meant approximating a bimodal distribution; in others, it referred to the distinctness of identified groups; and in yet others, it referred to the variety of held beliefs. Our project turned away from our own computational model and into sorting out the various phenomena called *polarization* into distinct concepts.

We elucidated nine senses of polarization with corresponding formal measures to demonstrate their distinctness. Five of the measures were based on the distribution of the whole population (spread, dispersion, converge, regionalization, and community fragmentation), whereas four measures were based on inter- and intragroup distributions (distinctness, group divergence, group consensus, and size parity; Bramson et al., 2016, 2017; Grim et al., 2012, 2014). These nine senses of polarization depend only on features of the distributions and are thus remarkably germane to a wide variety of problems and domains.



Bennett Holman

The first work was primarily conceptual, with formal measures only playing a clarifying role. We next applied our collection of measures to topics previously identified as polarizing by the General Social Survey dataset—specifically to questions on political views, religiosity, and abortion attitudes of the U.S. population from 1984 to 2012. We found that some cases of scholarly disagreement over whether Americans are polarized were driven by researchers invoking different concepts/measures of polarization. For example, attitudes on abortion maintain a clear bimodality that other ideological issues do not exhibit. Our expanded set of precise polarization concepts and measures brings greater clarity to discussions of polarization. These variants could not be identified using previous patchwork measures of polarization, and a more nuanced view of similarities and differences has implications for articulating system dynamics across disciplines.

Epistemic Success and Convergence

The various concepts of polarization bring with them corresponding concepts of convergence. Opinions converging at distinct points constitutes polarization while opinions converging at a central consensus constitutes the antithesis of polarization. At this point in our research, we went on to use that concept of consensus as one of two criteria in evaluating the functionality of collective problem-solving in general (Grim, Singer, et al., 2013). Convergence is whether and how quickly people in an epistemic community form a consensus from diverse views; epistemic success measures whether collective problem-solving achieves a correct answer (see, e.g., Lazer & Friedman, 2007; Mason, Jones, & Goldstone, 2008; Zollman, 2012). An emphasis on the latter concept in addition to the former eventually led us beyond our initial focus on polarization in particular to a wider modeling of social exploration and problem-solving in general.

Agent-Based Complex Systems Modeling

We discussed research methods that can integrate multidisciplinary theories and the multilevel factors that are involved in collective problem-solving and polarization. Agent-based, complex systems models are simulated multiagent systems in which multiple agents interact with each other simultaneously over time. Agents follow a few simple contingency rules. System-level properties emerge from a single rule, or combinations of different rules. This methodology is beneficial for conducting multidisciplinary research because it can establish the cross-level links between microlevel psychological mechanisms and macrolevel group polarization phenomena and can formalize cross-level interaction effects (Davis, O'Mahony, Gulden, Osoba, & Sieck, 2018). Similarly, Epstein (2008) pointed out that models can be the focal points of teams involving experts from many disciplines because researchers can incorporate the best domain expertise in a rigorous way. Furthermore, while assumptions often vary across different disciplines and theories, modeling forces researchers to make those assumptions explicit, reducing miscommunication and facilitating a rigorous study of their consequences.

Primary Research Contributions

Memes Versus Genes Versus Germs: Comparing Information-Transfer Mechanisms

One research project toward building a common groundwork aimed to investigate how memes as an epistemological information unit spread differently from germs and genes as epidemiological and genetic information units (Grim, Singer, Fisher, & Reade, 2015; Grim, Reade, Singer, Fisher, & Majewicz, 2010). We built the information transfer model for three kinds of information (i.e., germs, genes, and memes). Genes coded in DNA pass though reproduction networks. Germs contain genetic information in RNA and DNA that is spread through contact and infection. Memes carry propositional information and are transferred through learning and reinforcement on social communication networks. Simulation results indicate that the spread of memes is sensitive to the degree of *linkage* between subnetworks, whereas the spread of germs is sensitive to network structures. The spread of genes is robust across different network structures and subnetwork linkage patterns. Our work implies that there may be optimal community structures for knowledge communication where the linkage

Karen Kovaka

between different communities can expedite collective problem-solving and consensual knowledge formation. The results suggest that public health interventions should focus not only on epidemiological networks of contagion but on health-related information networks as well.

Belief Polarization in Different Ethnic Communities

Next, we turned our attention to the real social problem of health care information disparity between different ethnic groups (Grim, Thomas, et al., 2013). Information networks can vary between different ethnic communities, as can levels of trust in information from different sources. Thus, information about health and health care can also spread differently in different racial and ethnic communities. We particularly focused on a situation when information from a governmental source (Centers for Disease Control and Prevention) is conflicting with information from religious sources (church or religious leaders). We used empirical data from the Greater Pittsburgh Random Household Health Survey to construct health information networks for White and Black communities. White communities had a dense network with more connections to family and friends, and distrust of religious sources was prominent among those who have many informational connections with family and friends. Black communities had a sparse information network with fewer connections to family and friends. In black communities, a distrust of family, friends, and the government (Centers for Disease Control and Prevention) was more widespread among those who were isolated in the network.

Using our empirically driven networks with varying degrees of connections and trust levels, we constructed attitude update algorithms informed by social psychological rules of social influence (i.e., people change their health beliefs by social influence from whom they trust), and implemented the algorithms in a network dynamic model. We explored how the structure of the information network and inputs from different sources affect the belief configuration of the community over time. Simulation results showed different dynamic patterns of belief polarization in two communities when governmental sources and religious sources disagree. In the Black community, health-related beliefs became extremely polarized such that some completely endorse governmental information while others completely endorse information from religious sources. In the White community, most people came to hold centrist or extreme beliefs favoring governmental information, with only a small number of people completely endorsing religious sources. Public health care interventions can use these belief dynamics to optimize information flow across different ethnic communities.

Social Structures for Collective Epistemic Success

Once we realized the importance of network structures in belief dynamics from our empirically driven health information network study described above, we continued to investigate which social network structures are more efficient in achieving epistemic success for problems with an objectively correct answer (e.g., health care information, legal problems). We modeled different network structures of epistemic communities ranging from decentralized networks (ring or small world), through random and regular lattices, to highly centralized and completely connected networks (Grim, Singer, et al., 2013, p. 20, Figure 6). Simulation results indicated that a society is more likely to achieve epistemic successes when its communication network is decentralized as in a small world or ring rather than highly centralized or completely connected. Although referencing and stimulated by work in other disciplines—specifically, Mason et al. (2008) in psychology, Cangelosi and Parisi (2002) in computational linguistics, Lazer and Friedman (2007) in administrative science, and a variety of sources in biology and epidemiology—our work in this regard was most clearly set in the context of contemporary work in computational philosophy (e.g., Zollman, 2012) akin to work in economics (Bala & Goyal, 1998), computer science and information theory (Kleinberg, 2001).

Next, we turned to subjective problems in which epistemic success is defined by when a collective decision correctly reflects the majority's opinion. We developed a model grounded in political science—the Condorcet jury theorem for a democratic voting process, and Hong and Page (2004)'s "diversity trumps ability" study for a demo-

cratic debate process. Then, we explored whether two democratic processes (voting and/or debate) would successfully reflect the majority's opinion in a representative hierarchy similar to that possessed by most advanced modern democratic countries. We modeled various opinion pooling rules, from a direct democracy in which collective decisions are made by majority rule to a representative democracy in which collective decisions are made by elected officials representing a group of people (Grim et al., in press). Simulation results indicated that when collective decisions are made solely by a vote, direct majority voting is epistemologically superior to a representational structure. However, when collective decisions require discussion, deliberation among representatives has identical or slightly superior results to full deliberation among all participants.

Social Influence, Diversity, and Polarization

We have recently turned our focus to more sophisticated microlevel psychological processes. We extensively reviewed the social influence literature in the field of social psychology and modeled the contemporary theory of majority and minority influences using an agent-based model (Jung & Bramson, 2014, 2016; Jung, Bramson, & Crano, 2018). Simulations revealed that in the face of a strong conformity force toward the majority, indirect minority influence can spread a nascent idea to the whole society and change the status quo as long as group members have a high internal consistency drive.

In political science and other social scientific fields, random errors have been considered as an important source for diversity in a society (Bednar, Bramson, Jones-Rooy, & Page, 2010) as well as social change (Nowak & Lewenstein, 1996). We incorporated the random error process within our model and compared two mechanisms in terms of their consequences in diversity and polarization of opinions and the magnitude, speed, and frequency of social change. Simulation results indicate that both indirect minority influence and random errors produce social change and diversity, but with different patterns of complexity. With introducing random errors, a group has a small but persistent minority and goes through rare, but rapid and radical social change from one extreme to the other. With indirect minority influence, a group has persistent equally sized majority and minority factions, and all agents have uniquely different attitude compositions; social change occurs frequently but gradually and within a moderate range (Jung, Page, & Miller, 2017; Jung, Page, Miller, Bramson, & Crano, 2018).

Finally, we investigated the combinatory effects of different influence sources on polarization and consensus: (a) word-of-mouth, (b) deliberative groups, and (c) polarized media (Pulick, Korth, Grim, & Jung, 2016). We adapted schedules of reinforcement (Ferster & Skinner, 1957) to a computational model. We found that with varying reinforcement levels media influence alone polarizes public opinion whereas under group deliberation alone it converges to the center. Media influence and group deliberation interact to form public consensus not at the center but at one extreme.

Polarization via Rational Responses

In the social sciences and philosophy, belief polarization is typically viewed as a consequence of epistemic irrationality. Among social psychologists, the most popular views attribute polarization to biased evaluation and assimilation of evidence (see Lord et al., 1979), motivated reasoning (Taber, Cann, & Kucsova, 2009), individuals wanting to maintain their social identity in a group (Abrams et al., 1990), or attempts to avoid uncertainty (Gaffney, Rast, Hackett, & Hogg, 2014; Sherman, Hogg, & Maitner, 2009). In all of these cases, the factors that create polarization are not the sort of thing that can epistemically justify or rationalize agents' beliefs, so polarization is treated as a product of epistemic irrationality. To model how polarization might arise, we developed a model that takes inspiration from the hidden profile paradigm (Sohrab, Waller, & Kaplan, 2015; Stasser & Titus, 2003) from social psychology. Using a computational model, we can experiment with the full range of behavior-generating mechanisms, from completely rational agents to completely irrational agents. It would be difficult, or even impossible, to study this topic with human subjects.

In our model, agents can hold a limited number of arguments (e.g., a maximum of seven arguments; Miller, 1956) for or against some conclusion. Some arguments are shared and others are unique to individual agents. Each argument has a weight, which specifies how strongly it counts in favor or against the conclusion. An agent's belief is modeled as the sum of their argument weights. There are two key differences between our model and the hidden profile model. First, in our model the set of all arguments held by agents at a particular time point is only part of the whole set of arguments. This means that some arguments may never be discovered. In the hidden profile model, on the other hand, what is supported by all the information is always accessible if all group members successfully pool all the information and sort out the information among them. We believe this aspect of our paradigm better represents social epistemic processes in reality where a group may not have the information necessary to reach a correct answer even when they pool all the information they hold. Second, in our model each argument has a continuously valued weight indicating argument quality, whereas in the hidden profile model each piece of information is simply either relevant or irrelevant to problem-solving.

In our simpler simulations, in each round of the group discussion, one agent shares one argument and the shared

argument is heard by all the other agents in the group (i.e., there is perfect communication). Because agents have a limited memory, they need to forget one argument after they receive a new argument via group discussion. We tested three ways of forgetting: (a) forgetting randomly, where agents forget a randomly chosen argument; (b) forgetting the weakest argument, where agents forget their weakest argument regardless of what it supports; and (c) forgetting the weakest opposing argument, where agents forget the weakest argument that opposes their all-things-considered belief. When agents have limited memories and forget randomly or forget the weakest argument, the group always reaches a consensus. However, when agents with limited memories forget the weakest opposing argument, the group almost never converges and two subgroups emerge. We found similar results when agents are allowed to get arguments from outside of the group in addition to internal group discussion.

By appeal to the philosophical literature, we show that forgetting the weakest opposing argument does not have the features that make biased evaluation and assimilation irrational. We then give two arguments that show that this method is a rational way to manage one's memory (for the extensive epistemological discussion, see Section 4 of Singer et al., 2018). It follows that groups of agents can become polarized in virtue of everyone acting rationally in response to new incoming information.

Lessons Learned

Balance Between Sciences and Humanities

A lesson we learned is that a team's disciplinary composition and open-mindedness to different disciplinary assumptions are important, but that what is really critical for successful and effective multidisciplinary research practice on this kind of topic is the balance between the sciences and the humanities. Three scientific disciplines help us understand the way things are. Social psychology provides microfoundations of polarization. Political science provides meso- and macrolevel explanations. Complex systems science provides an excellent integrative framework both theoretically and methodologically. Science describes the social and physical world, but does not tell us how we should interpret and apply scientific knowledge to societies. That is where the humanities come in. Social philosophy and epistemology provide normative guidelines for our scientific research. In this vein, the team focuses on understanding that combinations of individuals' cognitive mechanisms and social structures can lead to epistemologically healthy societies.

A Core Group and a Fuzzy Boundary

A mix of strong and weak ties in research groups has been shown to generate a productive balance between exploration and exploitation in scientific research (Wang, 2016). We agree and believe that the reason that our team has been able to conduct its multidisciplinary research continuously, effectively, and creatively is that we have a core group with a fuzzy boundary. Having core members who are committed to the team is critical for its viability. After years of weekly meetings and discussions, researchers in the same team come to build a similar knowledge base. To some degree, this makes communication and research efficient. But it also can make a team environment stagnant and less creative. Although the team has core members who are strongly committed to collaborate in pursuing our research programs, both graduate and undergraduate students have made important contributions before moving onto other paths (Steven Fisher, Carissa Flocken, Sean McGeehan, Anika Ranginani, Christopher Reade, and Graham Sack). There is no demand that collaborators commit for the long-haul.

When new members have joined permanently or temporarily for some projects, we have experienced definite effects on both team climate and knowledge. First, while we brief a new member, we sometimes discover pieces of important information that have been neglected. Second, when a new member brings a new perspective, a new frame, and new knowledge to the group, old-timers adopt a divergent thinking style and are able to view problem spaces from broader perspectives. Also, the group sometimes adopts novel directions of research suggested by new members, which keeps the group fresh and interesting.

Three Models Project

Not all of our collaboration has been equally successful, nor have all of our projects had a smooth development. Here too lessons have been learned. The work that ultimately appeared as Bramson et al. (2016) and Bramson et al. (2017) was originally conceived as a "three models project," in which three prominent formal models of polarization (Axelrod, 1997; Hegselmann & Krause, 2002; Macy, Kitts, Flache, & Benard, 2003) were compared in terms of the specific patterns of opinion distribution they were and were not capable of producing, particularly with an eye to empirical results in the psychological literature (e.g., Lord et al., 1979). We assigned the writing of separate sections on each of the three models to three different subteams, with all collaborating on the general introduction. The result was an unwieldy and uncoordinated patchwork, a result immediately evident to all and a source of frustrated chagrin. The models at issue were so different that our disparate subteams had taken radically different approaches in different sections, emphasizing radically different features. Only much later, with a new overarching format of comparison

from Aaron Bramson, were we able to integrate our efforts. The lesson we have learned is that the apparent efficiency of dividing a paper into separate sections by different team members can compromise and undermine the benefits of full synchronous collaboration and communication on all aspects of a project throughout its development.

Future Directions and Empirical Validation

Our current model of rational polarization demonstrates how polarization might arise from rational information processing. Building from it, we plan to include other parameters into the model—path dependence, sharedness of arguments (majority or minority), diversity (Grim et al., 2019, in press), comparative contexts (intergroup and intra group), issue types (subjective or objective), hierarchical representation, and interaction communities (communication across social networks). This model and its associated extensions aim to shed light on the continuing political polarization in American politics. The national (Hopkins, 2018), cultural (Hetherington & Weiler, 2018), and representational (Broockman & Skovron, 2018) polarization of politics hinge on the kind of underlying dynamics that we hope to account for. Indeed, as Levendusky (2010) and Ahler and Broockman (2018) showed, not all polarization is bad, and in fact may, under some conditions, increase the representative merits of the political system.

Our approach offers novel insights into the field of social psychology. Most previous studies in attitude change and persuasion focus mainly on changes in general attitude when people are exposed to strong or weak persuasive messages, rather than the specific arguments involved. It is still unknown how people update their arguments and which arguments they would retain or discard. A series of experiments can be conducted to explicate how and when people update their arguments for a particular attitudinal topic during group discussion and debate, and how such argument updates influence overall attitude and belief.

Our recent project about forgetting process and polarization has inspired psychological studies conducted by the social psychologist member of our team. For example, her recently published paper on jury discussion indicates that group discussion can affect not only information presented during the discussion, but also information presented after the discussion (Kerr & Jung, 2018). Whether and how the recency effect of group discussion would cause polarization remains as a future research question.

Concluding Remarks

There have been increasing demands for more multidisciplinary research in scientific communities. Because different disciplines have been building their own system of knowledge for a long time on their own disciplinary assumptions and with their own vocabulary, multidisciplinary communication, not to mention multidisciplinary research, is inherently difficult. Emphasizing open-mindedness is important but not enough. We believe that it is important to have an agreement on what integrative framework a team wants to take. We also believe the right balance between the sciences and the humanities is critical if the goals of the team are to solve real-world problems and to contribute to a better and healthier society.

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