Research Statement

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My current research interests focus on the **modeling, analysis and control of network dynamical systems**, with applications particularly in social network systems. In what follows, I elaborate these research interests and briefly introduce my scientific background. Then I summarize my research contributions and outline my future research plan.

1 Area of Research: Social Networks Dynamics

Our society is deeply shaped by how people are organized and interact with each other. Different types of interpersonal relations and interactions constitute various complex social networks. Here "complex" often implies 1) the large scale of the networks; 2) the lack of well-quantified local details; 3) the highly nonlinear and random dynamic interplay among individual states, interpersonal relations, global information, and multiple layers of networks. As the result of such complexity, compared with other networks in natural or engineering sciences, quantifiable and predictable studies on social network systems exhibit their unique difficulties and have long been pursued by researchers in various areas. In the last decades, the rise of Internet and online social media provides a vast number of empirical data, which makes quantitative studies of social systems possible, and in the meanwhile has also deeply altered the pattern of how people interact with each other. In this era of information revolution, our society faces various unprecedented challenges with profound impacts on modern politics and economy, such as ideology polarization, the politicization of public debates, echo chambers and the spreading of misinformation. These challenges in turn bring urgent practical significance to the study of social network systems.

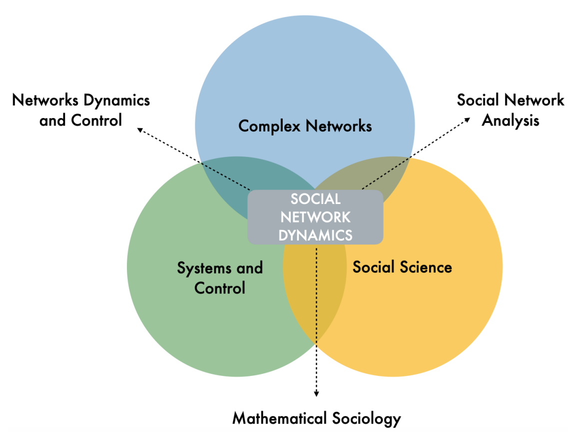

Fig. 1. A Venn diagram for different research areas related to social network systems.

Exploiting the progress in complex networks and data mining, the last decades have witnessed a rapid development of the research on the statistical and static features of social networks, in the framework of Social Network Analysis.

However, dynamical processes on/of social networks remain to be thoroughly studied. As an important theoretic framework in control theory, network multi-agent systems provide powerful mathematical tools, e.g., matrix analysis, graph theory, dynamical systems, and stochastic processes, for quantifiable and predictable research on dynamical processes in social network systems.

The fields of social network dynamics and control theory are on parallel mutually-beneficial paths. As mentioned above, numerous complex social network structures and processes can be fruitfully studied adopting the combined theories of networks, dynamical systems and control. On the other hand, better understanding of human behavior is of direct and critical importance in the study of some engineering systems, such as the cyber-physical-human systems, which consists of computers, cyber-physical devices, and people, communicating to each other.

2 Research Contributions

My research on modeling and analysis of social network dynamics spans a **complete spectrum**: dynamics on networks, i.e., the evolution of nodal states via social interactions; dynamics of networks, i.e., the evolution of social relations themselves; the dynamics interplay between nodal states and their interconnections.

2.1 Dynamics on Networks

Dynamical processes on social networks are extensively studied by researchers from different backgrounds. In control community, researchers mainly study two classes of processes: opinion dynamics and network propagation models. I have made some research achievement on both topics.

Rethinking the micro-foundation of opinion dynamics

Motivation and background:

- Nowadays public opinion formation faces **unprecedented challenges** such as opinion radicalization, echo chambers, and opinion manipulations. Realistic and predictive mathematical models play a fundamental role in obtaining reliable understanding of the mechanisms behind empirically observed opinion formation processes. Since interpersonal influences are highly complicated involving various cognitive and socio-psychological mechanisms, the **key challenge** in building predictive and tractable quantitative models of opinion dynamics is to identify the "salient features" that govern how individuals' opinions are influenced by each other, i.e., the **micro-foundation** of opinion dynamics.
- Most existing opinion dynamics models are based on the classic DeGroot model [1, 2], which assumes that individuals update their opinions by taking some **weighted averages** of their neighbors' opinions. Despite being able to explain some simple feature of opinion evolution, e.g., persistent disagreement [3–5], these models suffer from the **limitation in predictive power** in terms of capturing more sophisticated real-world phenomena.

Contribution to this research topic:

- We point out that the weighted-averaging opinion update mechanism, widely adopted by DeGroot model and all its extensions, implies a long-overlooked but non-negligibly **unrealistic implication**. Therefore, researchers might need to rethink the micro-foundation of opinion dynamics.
- By resolving this unrealistic feature in the framework of cognitive dissonance theory, we propose a novel opinion dynamics model based on a **weighted-median mechanism** instead. Such an inconspicuous change in microscopic mechanism, from weighted averaging to weighted median, leads to dramatic macroscopic consequences.
- **Experimental data validation** indicates that, compared with the averaging mechanism, predictions of individual opinion shifts by the median mechanism enjoys significantly lower error rates.
- Numerical studies indicate that, compared to other widely-studied models, our new model, despite its simplicity in form, predicts various important **realistic features** of opinion dynamics while the other models fail to, e.g., the vulnerability of socially marginalized individuals to opinion radicalization, the formation of steady multi-polar opinion distributions, and the vanishing consensus probability in larger and more clustered social groups.
- Theoretical analysis reveals that our model exhibits richer consensus-disagreement **phase transition** behavior dependent on more delicate and robust network structures.

- The novel weighted median model renovates our understanding of opinion formation processes and **extends the applicability** of opinion formation models to the setting of ordered multiple-choice issues, which are prevalent in modern-day public debates and elections.

Related paper: [WM-FB-GC-JH-FD:19] W. Mei*, F. Bullo, G. Chen, J. Hendrickx, F. Dörfler, "Rethinking the Micro-Foundation of Opinion Dynamics: Rich Consequences of an Inconspicuous Change", submitted, arXiv:1909.06474.

Dynamics of Network Propagation Processes

Motivation and Background: Epidemic spreading models have been a popular research topic in the control and computer science communities in the last decade and is now drawing special attentions during the COVID-19 pandemic. Numerous variations of the classic network susceptible/infection (SI), susceptible/infected/susceptible (SIS), and susceptible/infected/recovered (SIR) models have been proposed [6]. However, some early literatures on the network epidemic models in the 1970's [7, 8] do not receive enough attention from the recent works, and the basic dynamical properties of the classic network SI, SIS and SIR models have not been systematically characterized.

Contribution to this research topic: We provide some of the theoretic foundations underpinning the network SI, SIS, and SIR epidemics models.

- We review network epidemic spreading models for SI, SIS, and SIR settings. In each setting, we provide a comprehensive nonlinear analysis **analogous** to the corresponding well-known scalar case.
- For the SIS setting, we provide novel results on the computation and characterization of the **endemic state** (when the system is above the epidemic threshold), and present alternative proofs for some of its properties.
- For the network SIR setting, we propose **novel results** for transient behavior, threshold conditions, stability properties, and asymptotic convergence. In addition, we provide a novel iterative algorithm to compute the asymptotic state of the network SIR system.
- Inspired by the epidemic spreading models, we propose a class of epidemic-like propagation models for **multiple competing products** over arbitrary social networks. We then study a dynamic game where companies of the competing products seek for the optimal trade-offs between improving product qualities and advertisements.

Related paper: [WM-SM-SZ-FB:17] W. Mei*, S. Mohagheghi, S. Zampieri, and F. Bullo, On the Dynamics of Deterministic Epidemic Propagation over Networks, Annual Reviews in Control, 44:116-128, 2017.

[WM-FB:17] W. Mei* and F. Bullo, Competitive Propagation: Models, Asymptotic Behavior and Quality-Seeding Games, IEEE Transactions on Network Science and Engineering, 4(2):83-99, 2017.

[WM-FB:14] W. Mei and F. Bullo, Modeling and Analysis of Competitive Propagation with Social Conversion, In IEEE Conference on Decision and Control, Los Angeles, CA, USA, pp. 6203-6208, December 2014.

2.2 Dynamics of Networks

It has been extensively studied how individuals states evolve via local interactions embedded on social networks. However, less attention has been paid by researchers on how the social networks themselves evolve. In fact, dependent on the types of social relations/interactions and the underlying microscopic mechanisms, dynamics of social networks lead to various non-trivial macroscopic sociological phenomena. My research in this area focus on the dynamics of interpersonal appraisal networks leading to two types of group behavior: structural balance and collective learning, corresponding to the conflicts and collaborations in human groups respectively.

Dynamic Structural Balance Model

Motivation and Background:

- Structural balance theory describes allowable and forbidden configurations of the topology of **signed social networks** [9, 10].
- While previous studies focus mainly on the static theory of structural balance (i.e., the local and global configurations of balanced networks) [11–13] and opinion dynamics on structurally balanced/unbalanced networks [14], only a few models have been proposed to explain how an initially unbalanced network evolves to a balanced network [15–18].

- Previous dynamic models either suffer from the existence of unbalanced equilibria or **diverge** in finite time after achieving structural balance. It remains a valuable open problem to propose dynamic models, based on natural assumptions, that have certain desired bounded evolution and convergent properties.

Contribution to this research topic:

- We propose two discrete-time dynamical systems that explain how an appraisal network evolves towards social balance from an initially unbalanced configuration. These two models are based on two well-established socio-psychological mechanisms respectively: the **homophily** mechanism and the **influence** mechanism.
- Our main theoretical contribution is a **comprehensive analysis** of the dynamical behavior for both models. We establish the well-posedness and bounded evolution of the interpersonal appraisals and characterize the set of equilibrium points. Moreover, we establish convergence of the appraisal network to a final equilibrium network satisfying structural balance. In addition to our theoretical analysis, we present numerical results on the mediation and globalization of local conflicts, the competition for allies, and the asymptotic formation of a single versus two factions.
- Since all the aforementioned models either diverge in finite time, or suffer from the existence of unbalanced equilibria, or only work for complete graphs, we further extend our modeling and analysis to general **non-all-to-all graphs**. We first propose two intuitive definitions of structural balance in non-all-to-all graphs: the triad-wise balance and the two-faction balance, and then establish the connections between this two definitions, i.e., on what graph-theoretic conditions these two definitions are **equivalent**. For the first time, we propose two dynamic models of appraisal networks that guarantee **almost-sure convergence** to these two notions of structural balance respectively. Further numerical study leads to meaningful insights on whether multilateral relations alleviate or exacerbate conflicts in social networks.

Related paper: [WM-PCV-NEF-FB:18] W. Mei*, P. Cisneros-Velarde, N. E. Friedkin, and F. Bullo, Dynamic Social Balance and Convergent Appraisals via Homophily and Influence Mechanisms, Automatica, 110: 108580, 2019.

[WM-GC-FD] W. Mei, G. Chen*, F. Dörfler, Structural Balance and Interpersonal Appraisals Dynamics: Beyond All-to-All and Two-Faction Networks, in preparation (manuscript available upon request).

Dynamic models of appraisal networks and collective learning

Motivation and background:

- Researchers in sociology, psychology, and organization science have long been studying the inner functioning and performance of teams with multiple individuals engaged in tasks. *Transactive memory System* (TMS) is one of the well-established conceptual models of team structure and performance in organization science [19–22]. To put it simply, TMS characterizes 1) the team members' mutual perceptions of individual expertise; 2) the division of labor based on the *collective knowledge* on the distribution of expertise.
- Empirical research demonstrates a strong positive relationship between the development of a team's TMS and the team performance.
- Despite extensive qualitative and empirical studies on team performance and structures, sociologists have never explicitly related TMS to any **internal structure** of teams.

Contribution to this research topic:

- Based on the abstraction of qualitative statements in sociological literature, we propose for the first time a class of **multi-agent models** that deconstruct the concept of TMS in terms of networks in teams. We model **from the scratch** how a group of individuals asymptotically learn the optimal task assignment by decentralized interactions along executing a sequence of tasks.
- The core idea is that the ***appraisal network*** acts as the team's basic inner structure and the development of TMS is thereby modelled as the dynamics of the appraisal network.
- The closely-related proposed models have increasing complexity, starting with a centralized manager-based assignment and learning model, and finishing with a social model of interpersonal appraisal, assignments, learning, and influences.
- As indicated by our models, **rational global behavior** could emerge from **instinctive local interactions**. In addition, the **collective knowledge** on the optimal task assignment could reside in the interpersonal appraisal network, instead of in any single team member's mind.

- We further extended our models by allowing for more degrees of freedom. The extended new model is a closed-loop network dynamics system that combines local replicator dynamics, describing how individuals adjust their appraisals of others based on observations of others' individual performances, and compartment flow of workload via the interpersonal appraisal networks. This new model could be considered as a **socio-inspired** optimal economic dispatch algorithm that is plug-and-play and highly adaptive to changes of problem dimension via only local adjustments.

Related paper: [WM-NEF-KL-FB:18] W. Mei*, N. E. Friedkin, K. Lewis, and F. Bullo, Dynamical Models of Appraisal Networks Explaining Collective Learning, IEEE Transactions on Automatic Control, 63(9):2898-2912, 2018.

[EYH-DP-WM-FB:20] E. Y. Huang, D. Paccagnan, W. Mei*, and F. Bullo, Assign and Appraise: Achieving Optimal Performance in Collaborative Teams, submitted to IEEE TAC, arxiv.org/abs/2008.09817

2.3 Dynamic Interplay between dynamics on and of networks

The co-evolution of nodal states and their interconnections is a promising but relatively less touched research topic. My research in this area covers the dynamic **interplay** between opinion dynamics and appraisal network dynamics.

Motivation and background: In social systems, the evolution of interpersonal appraisals and individual opinions are not independent processes but intertwine with each other. Despite extensive studies on both opinion dynamics and appraisal dynamics separately, no previous work has ever combined these two processes together.

Contribution to this research topic:

- We propose a novel and intuitive model on the interplay between homophily-based appraisal dynamics and influence-based opinion dynamics, and analyze this new model's dynamic behavior.
- Compared with previous works that explain the emergence of social balance via person-to-person homophily mechanism, our model provides an alternative explanation in terms of the person-to-entity homophily mechanism.
- In addition, our model also describes how individuals opinions on multiple irrelevant issues become correlated and converge to modulus consensus over time-varying influence networks.

Related paper: [FL-SC-WM-FD-MB:20] F. Liu, S. Cui, W. Mei*, F. Dörfler, and M. Buss, Interplay Between Homophily-Based Appraisal Dynamics and Influence-Based Opinion Dynamics: Modeling and Analysis, IEEE Control Systems Letters, 5(1):181-186,2020.

3 Future Research Agenda

In the future, I will deepen my study on social network dynamics, and, in the meanwhile, extend my research to the modeling, analysis, and control of network dynamical systems in other context.

Modelling and analysis of opinion politicization

Beyond consensus and disagreement, mathematical modeling can be used to explain more sophisticated and meaningful phenomena of opinion dynamics, e.g., **opinion politicization**. Opinion politicization means that people's **opinions** on a certain issue are highly correlated with their political **ideologies**, even though the issue being discussed is not logically related to politics at all. Nowadays the US society has exhibited clear trends of opinion politicization on many non-political issues, e.g., whether hydroxychloroquine is effective against COVID-19 or whether wearing face masks helps prevent the spread of coronavirus. Mathematical modeling plays a critical role in investigating possible socio-psychological mechanisms leading to opinion politicization, as well as effective intervention methods.

We have done some tentative modeling work based on **graphon games** and **population dynamics**, which has already shed light on some meaningful insights. In this preliminary model we construct, individuals are modelled as continuum and the population state is described by the two-dimension distribution over opinion and ideology spectra respectively. Individuals in the population consider others with similar ideologies as friends, while consider those with very different ideologies as enemies. Individuals change their opinions by taking the **best responses** that minimize certain cognitive dissonance caused by disagreeing with friends and agreeing with enemies. Simulation results on this preliminary model indicate that opinion politicization is more likely to emerge in societies with more **bi-polarized** ideology distributions or **less tolerant** individuals. Further modeling work is needed to simplify the model we propose and make it mathematically tractable. After that, theoretical analysis and empirical-data validation could both be pursued.

Best-response opinion dynamics from a unified viewpoint

As mentioned in the derivation of the weighted-median opinion dynamics [23] and also in some earlier literature [24,25], opinion dynamics could be interpreted as individuals' best response to reduce their **cognitive dissonances** generated by disagreeing with their social neighbors. I plan to study opinion dynamics as best responses to various forms of cognitive dissonance functions, their respective dynamical behavior, and possible empirical validations. For example, given the influence matrix, the most parsimonious form of the individual cognitive dissonance function could be

$$u_i(x) = \sum_j w_{ij}|x_i - x_j|^\alpha, \quad (\alpha > 0) \quad \text{for any } i,$$

and individuals' opinion updates are given by

$$x_i^+ \in \text{argmin}_{z\in\mathbb{R}} \sum_j w_{ij}|z - x_j|^\alpha.$$

Here the parameter α has a very clear sociological interpretation: $\alpha > 1$ implies that distant opinions are more attractive, e.g., $\alpha = 2$ for the DeGroot model; $\alpha < 1$ implies that similar opinions are more attractive; $\alpha = 1$ is the neutral hypothesis. It is interesting to study the following open question: for different values of α, what are the conditions for **almost-sure consensus and almost-sure disagreement** respectively? These must be some conditions on the network structure, e.g., the network connectivity for the case of $\alpha = 2$ and maybe some more delicate structure for other values of α. We already know the corresponding conditions when $\alpha = 1$ [23]. We further **conjecture** that the conditions are the same for any $\alpha > 1$ (and also the same for any $\alpha < 1$), but rigorous mathematical analysis needs to be conducted.

Seeking for the "best" opinion dynamics

As the empirical data of human-subject experimented cited in [23] shows, **further parameterizations** of the weighted-median opinion dynamics model, e.g., inertia in opinion updates and attachment to initial opinions, significantly improve the fit to data. All of these have before been studied for the DeGroot Model. It is natural to now seek the best model (in terms of fitting empirical data as well as best in terms of microscopic foundations) by introducing to the weighted-median model various **meaningful extensions** that used to be introduced to the DeGroot model. For example, researchers have introduced **antagonistic relations** to the DeGroot model and analyzed two different but related models: the opposing negative dynamics (also known as the Altafini model) and the repelling negative dynamics [14]. Similar extensions can be made to the weighted-median model. Actually, we have conducted thorough theoretical analysis of the *opposing negative weighted-median dynamics* and obtained some very exciting results. For example, our new model **resolves a long-existing unrealistic prediction** of the Altafini model that all the individuals' opinions converge to 0 as long as the signed influence network is strongly connected and structurally unbalanced. Such unrealistic behavior no longer exists if we combine the opposing negative dynamics with the weighted-median model instead of the DeGroot model. Moreover, numerical studies also lead to some insightful results, e.g., the **final opinion distributions** are more dispersed in influence networks with higher levels of **frustration**. Given all the results obtained, we are convince of the research value of introducing antagonistic relations to weighted-median opinion dynamics and we plan to further analyze the model combining the weighted-median dynamics with the **repelling negative dynamics**, which is more challenging and would probably lead to more insightful sociological interpretations.
Related paper: [BW-WM-CA-FD:20] B. Wang, W. Mei*, C. Altafini, F. Dörfler, Weighted-Median Opinion Dynamics with Antagonistic Relations, working paper.

Socio-inspired control for engineering systems

Modelling of human team behavior could be inspiring for the design of decentralized robots control systems. For example, in the paper on collective learning [26], we have proposed a model describing how a team of individuals achieve **optimal workload division** via local appraisal dynamics. This social dynamics also solves the economic dispatch problem in engineering in a decentralized manner. The type of tasks considered in [26] is perhaps the simplest: The workload can be arbitrarily decomposed into any n pieces and assigned to each person. In real-world scenarios, team tasks could be more complicated. For example, a task can have a **discrete nature** such that different individuals or different subgroups of individuals need to play different roles. Models of collective learning for such type of team tasks could be naturally applied to the design of engineering systems, e.g., the multi-target tracking tasks for robots teams.

References

1. J. R. P. French Jr., "A formal theory of social power," *Psychological Review*, vol. 63, no. 3, pp. 181–194, 1956.
2. M. H. DeGroot, "Reaching a consensus," *Journal of the American Statistical Association*, vol. 69, no. 345, pp. 118–121, 1974.
3. D. Acemoglu, G. Como, F. Fagnani, and A. Ozdaglar, "Opinion fluctuations and disagreement in social networks," *Mathematics of Operation Research*, vol. 38, no. 1, pp. 1–27, 2013.
4. R. Hegselmann and U. Krause, "Opinion dynamics and bounded confidence models, analysis, and simulations," *Journal of Artificial Societies and Social Simulation*, vol. 5, no. 3, 2002. [Online]. Available: http://jasss.soc.surrey.ac.uk/5/3/2.html
5. N. E. Friedkin and E. C. Johnsen, "Social influence and opinions," *Journal of Mathematical Sociology*, vol. 15, no. 3-4, pp. 193–206, 1990.
6. C. Nowzari, V. M. Preciado, and G. J. Pappas, "Analysis and control of epidemics: A survey of spreading processes on complex networks," *IEEE Control Systems*, vol. 36, no. 1, pp. 26–46, 2016.
7. A. Lajmanovich and J. A. Yorke, "A deterministic model for gonorrhea in a nonhomogeneous population," *Mathematical Biosciences*, vol. 28, no. 3, pp. 221–236, 1976.
8. H. W. Hethcote, "An immunization model for a heterogeneous population," *Theoretical Population Biology*, vol. 14, no. 3, pp. 338–349, 1978.
9. F. Heider, "Social perception and phenomenal causality," *Psychological Review*, vol. 51, no. 6, pp. 358–374, 1944.
10. ——, "Attitudes and cognitive organization," *The Journal of Psychology*, vol. 21, no. 1, pp. 107–112, 1946.
11. J. Leskovec, D. Huttenlocher, and J. Kleinberg, "Signed networks in social media," in *Int. Conf. on Human Factors in Computing Systems*, Atlanta, USA, 2010, pp. 1361–1370.
12. M. G. King, "Structural balance, tension, and segregation in a university group," *Human Relations*, vol. 17, pp. 221–225, 1964.
13. H. F. Taylor, *Balance in Small Groups*, ser. Sociological Concepts, Methods and Data Series. Van Nostrand Reinhold, 1970.
14. G. Shi, C. Altafini, and J. Baras, "Dynamics over signed networks," *SIAM Review*, vol. 61, no. 2, pp. 229–257, 2019.
15. S. A. Marvel, J. Kleinberg, R. D. Kleinberg, and S. H. Strogatz, "Continuous-time model of structural balance," *Proceedings of the National Academy of Sciences*, vol. 108, no. 5, pp. 1771–1776, 2011.
16. V. A. Traag, P. V. Dooren, and P. D. Leenheer, "Dynamical models explaining social balance and evolution of cooperation," *PLoS One*, vol. 8, no. 4, p. e60063, 2013.
17. A. van de Rijt, "The micro-macro link for the theory of structural balance," *Journal of Mathematical Sociology*, vol. 35, no. 1-3, pp. 94–113, 2011.
18. T. Hiller, "Friends and enemies: a model of signed network formation," *Theoretical Economics*, 2016, to appear. [Online]. Available: http://EconPapers.repec.org/RePEc:the:publsh:1937
19. D. M. Wegner, "Transactive memory: A contemporary analysis of the group mind," in *Theories of Group Behavior*, B. Mullen and G. R. Goethals, Eds. Springer, 1987, pp. 185–208.
20. D. W. Liang, R. Moreland, and L. Argote, "Group versus individual training and group performance: The mediating role of transactive memory," *Personality and Social Psychology Bulletin*, vol. 21, pp. 384–393, 1995.
21. K. Lewis, "Measuring transactive memory systems in the field: Scale development and validation," *Journal of Applied Psychology*, vol. 88, no. 4, pp. 587–604, 2003.
22. S. Y. Choi, H. Lee, and Y. Yoo, "The impact of information technology and transactive memory systems on knowledge sharing, application, and team performance: A field study," *Management Information System Quarterly*, vol. 34, no. 4, pp. 855–870, 2010. [Online]. Available: http://www.jstor.org/stable/25750708
23. W. Mei, F. Bullo, G. Chen, J. Hendrickx, and F. Dörfler, "Rethinking the micro-foundation of opinion dynamics: Rich consequences of an inconspicuous change," *arXiv preprint arXiv:1909.06474*, 2020.
24. P. Groeber, J. Lorenz, and F. Schweitzer, "Dissonance minimization as a microfoundation of social influence in models of opinion formation," *Journal of Mathematical Sociology*, vol. 38, pp. 147–174, 2014.
25. D. Bindel, J. Kleinberg, and S. Oren, "How bad is forming your own opinion?" *Games and Economic Behavior*, vol. 92, pp. 248–265, 2015.
26. W. Mei, N. E. Friedkin, K. Lewis, and F. Bullo, "Dynamic models of appraisal networks explaining collective learning," *IEEE Transactions on Automatic Control*, vol. 63, no. 9, pp. 2898–2912, 2018.