Networks in Economics
Remarks
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Prepared for the Econometric Society World Congress in Montreal August 2015

The past fifteen years has seen a burst in research on the economics of networks. Researchers have been studying a wide range of economic settings, and in each case, links between individuals arguably play critical roles in individual and aggregate outcomes. The following are some examples, with specified settings and links: peer effects with friendship links, innovation/research and development with links between researchers and colleagues, local public goods with geographic and social links, oligopoly and firms' interlinked markets, macroeconomic shocks and supply chain links, information transmission and people's social links, banking and links due to cross-holdings, and markets and links between buyers and sellers.

The mathematical structure of networks ties together all this research. In a network, agents have pairwise "links" that affect their dealings. These links collectively give the "adjacency matrix," also called the "graph," or the "network," that impacts outcomes for all agents. At the individual level, an agent's payoffs depend directly on the actions of her "neighbors," i.e., the agents to whom she is linked. Distant agents also shape payoffs and incentives to the extent they are indirectly linked, by "paths" in the network.

These remarks give a bird's eye of this research, providing a road map to bring together the detailed accounts of the empirical and theoretical research provided by the two papers in this session.[1] Following the road map, these remarks give a whirlwind tour of research objectives and themes and present challenges for future studies.

Research papers in this area typically begin with documenting an economic outcome of interest and recognizing that a network. underlies this outcome. Figure 1 gives a road map. Starting at the top, a theoretical study typically posits pairwise links between N agents that form a network G. An empirical study will also typically begin with data on the links that make up the network, i.e., who is linked to whom in the relevant population. There are then two black boxes to be filled in. The first box concerns how networks shape outcomes, i.e., the theory and empirics of how individual actions, given a network, lead to the economic outcome. The second black box concerns network formation, i.e., how links come about in the first place.

1. See the presented papers (de Paula (2016) and Goyal (2016)) for extensive references; only a few illustrative articles are cited here. For further reading, the forthcoming *Oxford Handbook on the Economics of Networks* (Bramoullé, Galeotti, and Rogers, 2016) provides a compendium of detailed papers reviewing the literature.

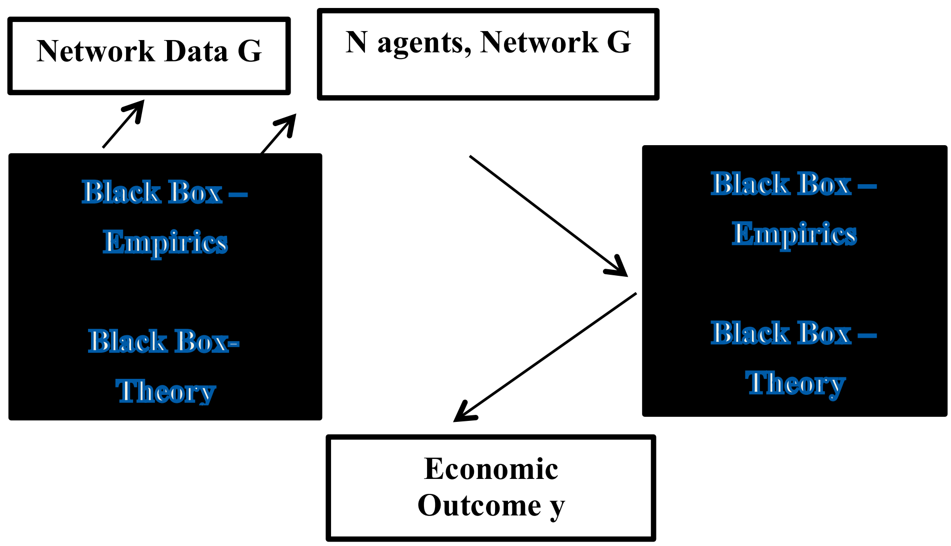

Figure 1. Road Map of Research in the Economics of Networks

Research efforts fill in (parts of) these black boxes, as outlined in Figure 2.

Networks Shape Outcomes: Starting with the black box on the right, the first track of research considers how given links between agents and the overall network structures shape individual and aggregate outcomes. Econometric research develops techniques to use network data to identify peer effects; consider the impact of agent 1 on agent 2. The actions of agent 3 who is linked to 2, but not to agent 1, can serve as an instrument for the impact of original relationship. Theoretical research develops games played on networks. Agents strategically choose actions (y_1,y_2, y_3, ...) as individual payoffs depend on neighbor's actions. The equilibrium of the game gives the overall economic outcome y.

Network Formation: The second track of research begins to fill in the black box on the left to considers how links are formed. Since actions of neighbors affect payoffs, people would have the incentive to make and break links. To capture this possibility, theorists develop models of strategic link formation. Empirical researcher study the statistical patterns that would emerge from such processes. Research also considers "mechanical" network formation processes, where agents links are generated by some random process.

To give a sense of the material covered in the two papers presented in the session: Goyal (2016) focuses on the two areas of theoretical research (in the lower halves of each black box) and de Souza focuses on the two areas of the empirical research (in the upper halves of each black box).

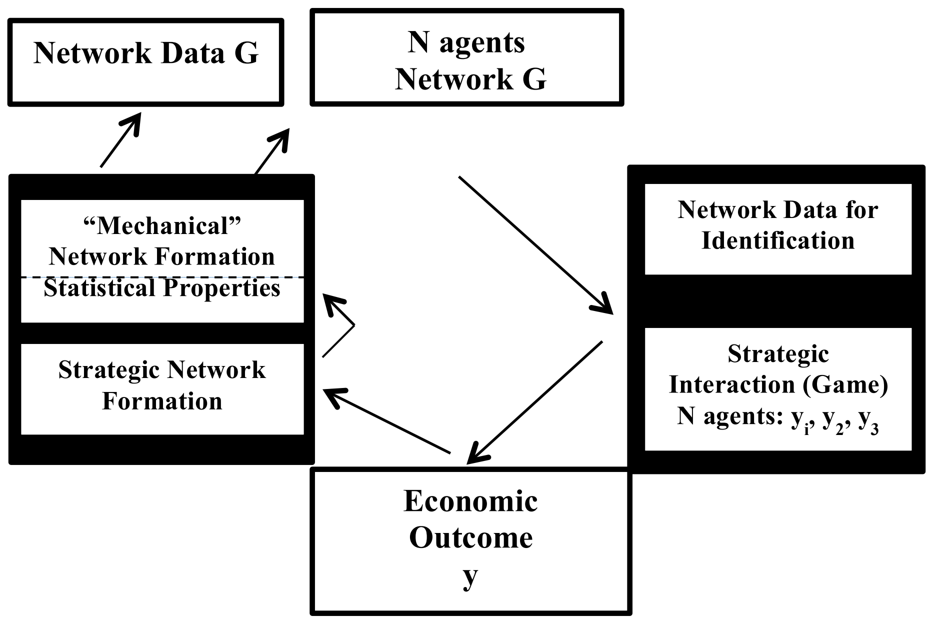

Figure 2. Filling in the Black Boxes

In all of these efforts, researchers often must develop new techniques and methods. Networks are discrete mathematically and the analysis of networks does not lend itself easily to traditional tools used in economics such calculus. The computational complexity of networks also requires new of statistical methods. To have a sense of these efforts, again follow the outline of this research in Figure 2, starting from the right.

Networks Shape Outcomes: In the econometric research on exploiting network data to identify social interactions, sufficient conditions involve the linear independence of powers of a network graph (Bramoullé, Djebbari, and Fortin (2009)). For strategic interaction on given networks, researchers must specify actions, game structure, and payoffs that incorporate the network structure. Researchers posit new games of local public goods, bargaining, price-setting, and collaboration take into account the combinatorics of links.

Network Formation: For strategic formation of networks, new equilibrium concepts take into account links and the complexity of the network setting. For example, since links are formed by pairs of agents, "pairwise stability" gives an alternative to Nash equilibrium. In a dynamic game, since completely forward-looking agents seem unrealistic, agents are posited to play myopic best replies, which lead (possibly) to a convergent set of networks. Ërdos-Rény random graphs and the generalization to exponential random graphs are prominent mechanical models of network formation, where each agent is linked to another probabilistically. Features of graphs are then analyzed by maximum likelihood and Markov Chain Monte Carlo (MCMC) methods.

The primary objective of all this research is to uncover network properties that determine individual and aggregate outcomes. To illustrate, there is perhaps now one setting that has been sufficiently well-studied to take us around the full circle of the map (with results from each of the speakers in this session). Consider peer effects or local public goods and more generally the set of models that all share an underlying structure where agents' optimal action is linear in his neighbors' actions.

Networks Shape Actions: Starting on the right, first, network data can identity peer effects when the network is sufficiently "sparse" (de Paula, Rasul, and Souza (2015)). In a strategic game on a network, individual actions are proportional to their Bonacich centralities, which give the weighted sum of the paths in a network starting from that individual (Ballester, Calvó-Armengol, and Zenou (2006)). The lowest eigenvalue of the network determines the equilibrium set, giving the critical measure of the overall extent of strategic substitutabilities (Bramoullé, Kranton, and D'Amours (2014)).

Network Formation: For network formation, in a model of local public goods where agents choose directed links simultaneously with actions, stars are Nash equilibrium outcomes; one agent is providing the local public good (Galeotti and Goyal (2010)). In a peer effect setting, models where agents can choose directed links gives stronger predictions that better match friendship data (Badev (2013, Melev (2013)).

While collectively researchers have greatly advanced the economics of networks, several challenges remain. The first set of challenges are perhaps most obvious and related to similar issues in other fields. The second set are perhaps particular to the study of networks.

The first set of challenges concerns multiple equilibria and identification. First, multiple equilibria arise in many games played on networks and in network formation games. Both in theory and empirics, researchers are already addressing this challenge by developing equilibrium refinements and computational and statistical methods to estimate outcomes. Second, beyond the concerns from multiple equilibria, identifying a network effect per se remains an empirical challenge when data is particularly light on individual characteristics. Since networks are endogenous, an individual might occupy a particular position within a network because of characteristics (such cognitive and non-cognitive skills) that are also directly related to the economic outcome of interest (such as success in school).

The second set of challenges concerns more deeply the overall research agenda and what can be learned from the economic analysis of networks. First, when studying network settings, researchers must pay close attention to which of the many possible connections between individuals are relevant for the economic outcome at hand. For example, in the study of peer effects, the available data might enumerate school friendships. But school friendships might not be critical to a student's educational and health outcomes. Enemies (or bullies) might be critical, or students who set the tone for the entire school, such as star athletes. The relevant links might be "virtual," and in general researchers are challenged to uncover the relationships that actually matter, and which relationships matter is, of course, itself an empirical question. The specification of empirical and theoretical models should rely on detailed descriptions of the environment, perhaps in literatures other than economics.

The second of these deeper challenges lies in the economic interpretation of the network features which emerge from our analyses. The holy grail in much of this research is to uncover some general empirical or theoretical regularity that is applicable to any network or any network data set. Eigenvalues, centrality measures, network structures such as stars or nested split graphs, all appear in results. The question then become: What insights to these mathematical features lend to our understanding of the social and economic world? How do these mathematical expressions relate to observed patterns of interaction? To answer these questions, economists could again learn from researchers in other fields such as physics, sociology, and computer science, who are engaged in such pursuits as defining network notions of communities and constructing algorithms to find communities given network data.

Citations

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