Network theory and social economics - a promising conjunction?

Gräbner, Claudius and Heinrich, Torsten and Kudic, Muhamed

Institute for Institutional and Innovation Economics (IINO), University of Bremen, Bremen, Germany; and, Institute for New Economic Thinking (INET), University of Oxford, Oxford, UK; and, Stifterverband für die Deutsche Wissenschaft, Wissenschaftsstatistik, Essen, Germany

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Network theory and social economics – a promising conjunction?

Claudius Gräbner*　　Torsten Heinrich†　　Muhamed Kudic‡

Abstract

Socio-economic systems are characterized by the properties of participating individuals and by the structure of the interactions and relations among them. Not adequately reflecting upon this structure usually leads to a deficient understanding of both the individual parts, and the system as a whole. Here we argue that therefore a closer relationship between socio-economics and network science is expedient. But for this to happen, a common language for the two fields is required. Against this backdrop we discuss examples of what has been accomplished by studying socio-economic systems with network theoretic methods and highlight potential contributions of socio-economists to this field. We identify a high thematic overlap in network theory and socio-economic literature and conclude that both socio-economists and network theorists could benefit greatly from a closer relationship between the two fields. We highlight, however, the need for adopting graph theory as a common language.

(148 words)

Key words: complex systems, innovation networks, structuration processes, network dynamics, evolutionary economics

*Institute for Institutional and Innovation Economics, University of Bremen, Germany. Email: graebnerc@uni-bremen.de.

†Mathematical Institute and Institute for New Economic Thinking, University of Oxford, Oxford, UK. Email: torsten.heinrich@maths.ox.ac.uk.

‡Institute for Institutional and Innovation Economics, University of Bremen, Germany. Email: kudic@uni-bremen.de.

1 Why study structuration processes and the dynamics of networks?

Interactions are an essential feature of every socio-economic system. Consequently, socio-economic systems are characterized not only by the attributes of the individuals but also by the structural properties of the system into which they are embedded. Not adequately reflecting upon these structural properties of the system usually leads to an deficient understanding of the processes and entities at the individual and aggregated level, and consequently of the system as a whole [Gräbner and Kapeller, 2017]. In other words, it is often important to know who interacts with whom, who owns which company or who are the central actors in a community.[1]

In this paper, we discuss how an integrative approach to socio-economic networks can address these challenges. We argue that such an approach should be built upon both social economics and network science. While social economics has always been concerned with the study of socio-economic mechanisms, the value base of social norms and institutions, and the relationship between social and economic aspects of society, the interdisciplinary field of network science has emerged in the last three decades and focused on the empirical investigation of the structure of natural, social, and artificial systems. We show how these two fields can effectively complement each other in explaining structuration processes i.e. the mechanisms driving the dynamics of socio-economic networks, and the functioning of complex socio-economic systems.

Socio-economists can benefit from this relation by exploiting the formalisms of network theorists. While the importance of the interaction structure has been apparent to socio-economists for many years, only the development of modern network theory provides the means to systematically and quantitatively investigate network structures. It provides a "language" to describe networks as well as mechanisms and processes operating on - and through - them (see table 1 and figure 1 for some of the basic vocabulary of this language). Such a (formal) language is needed by any approach that tries to understand socio-economic problems from a realist perspective because many important socio-economic mechanisms operate via the structure of relations and interactions and mere words are not accurate enough to describe these structures adequately.

The new language of network theory allows to ask more specific and concrete questions, such as: "what kind of relational structure facilitates the emergence of trust among individuals in larger communities?". Furthermore, it allows for a whole range of new empirical applications, such as the question of who owns and leads big transnational companies. Such work helps to identify many empirical regularities that - without such a formal language - would remain hidden.[2]

Network theorists could equally benefit from a closer collaboration between the two fields. Network theory as a mere tool is largely agnostic with respect to causal relationships in the formation of network structure and mechanisms on it. While network scientists have identified some striking empirical regularities of socio-economic networks (e.g. the fact that most companies are controlled by a small number of core players [Vitali et al., 2011]),

[1][Gräbner and Kapeller, 2017] identified the non-consideration of relations as one of four compositional fallacies that prevent the understanding of any social system consisting of several parts making up a social 'whole'. See this article for further meta-theoretical arguments supporting this claim.

[2]We introduce several of these regularities in section 3.1.

they usually have little to say about either policy implications or socio-economic interpretations of these regularities. Also, the theoretical explanations of why and how actors interact and how these processes themselves can change the network topology are still rather rudimentary and simplistic. Rules, norms, and institutions, for example, are very likely to play an important role for the structuration of any socio-economic system. Yet they are barely considered by network scientists. By contrast, socio-economists can provide theoretical contributions on these phenomena, offer missing interpretations of empirical results and motivate further empirical investigations of rules, norms and institutions. By this they can contribute to a crucially needed *mechanismic* understanding of socio-economic networks.

Mechansmic explanations are distinct to instrumental and hermeneutic explanations in that they propose particular *mechanisms* that have led to the creation of the network [Bunge, 2011]. By this they provide a much deeper insight into the system under investigation than the alternative modes of explanation because they not only illustrate *what* is the state of the system under investigation, but also *why* the system is in this particular state.[3] Mechanismic models for social networks represent one key avenue for further research to which social economists may contribute.

Aside from highlighting the potential of the integrated perspective outlined above, the paper contributes to the contemporary network literature in at least two more ways: Firstly, we address the intellectual roots of network research in mathematics, economics, sociology and related disciplines. This provides the foundation for the potential integration of socio-economic and network theoretical perspectives on networks.[4] Secondly, we identify a number of highly promising avenues for future research at the intersection of these two strands of research.

Before giving an outlook we will consider the following motivating example:[5] Empirical research has shown that a firm's positioning in the network of research alliances affects its innovation outcomes [Powell et al., 1996, Kudic, 2015]. This position is, however, not the only determinant of a firm's innovativeness: institutional, organizational, technological, geographical and cultural factors matter as well [Boschma, 2005]. Moreover, [Whittington et al., 2009] have shown for the US Life Science industry that the above outlined proximity dimensions can be independent,complementary or substitutional in their effect on innovation performance: for a firm, for example, being culturally well adapted to their environment significantly affects the relationship between network centrality and firm-level innovative performance. This illustrates that in practice it is usually necessary to integrate the contributions of both network scientists and social economists to understand the problem at hand.

In the remainder of the article we first introduce the historical and theoretical concepts in the interdisciplinary field of network research (Section 2). In Section 3 we then present an overview of structural regularities and dynamics of socio-economic networks that were identified using the formal language of network science. We

[3] See [Gräbner and Kapeller, 2017] for a more detailed epistemological and ontological discussion of the concepts of *mechanismic explanations*.

[4]

[5] You may consult the online appendix for an overview of successful applications of network theory to economic questions.

conclude in Section 4 with some remarks on limitations of contemporary network research, potential contributions by socio-economists and fruitful avenues for future inquiry.

2 Theoretical roots of contemporary network research in economics and related disciplines

We start with clarifying the historical roots of contemporary networks research. We show that networks have been an important research subject in both the social and natural sciences long ago (Section 2.1). Of particular importance was the discussion in economics and sociology on the origin of so called *hybrid organizational forms*, i.e. organizational forms between the ideal types of markets and hierarchies, that we discuss more closely in Section 2.2.

2.1 The origins of network research

Structuration and the inherent dynamics of networks was already discussed in early writings in sociology, economics and other fields, even though the term "network" is often not explicitly used. This section reviews these early approaches in order to both introduce the constitutional theoretical concepts and analytical tools of network theory and to clarify the historical origins of contemporary network research. These historical origins encompass the fields of mathematics, economics, and sociology. We discuss these origins one by one.

2.1.1 A glance over the fence – roots of network research in mathematics

In the early 18^{th} century mathematicians became interested in what later became known as graph theoretical problems. In its most basic sense, graph theory is concerned with abstract mathematical structures which can be fully described by limited number of lines (also called ties or edges) between a well-defined set of objects (also called nodes or vertices) - see Table 1 and Figure 1 for an overview over basic graph theoretic terms and concepts. The first graph theoretical problem – known as the seven bridges of Königsberg - was solved by Leonard Euler in 1736. He was able to *prove* that it was impossible to cross all bridges of Königsberg exactly once.[6] Since then, graph theory has developed greatly with many crucial problems solved and important methods developed only in the 20^{th} century.

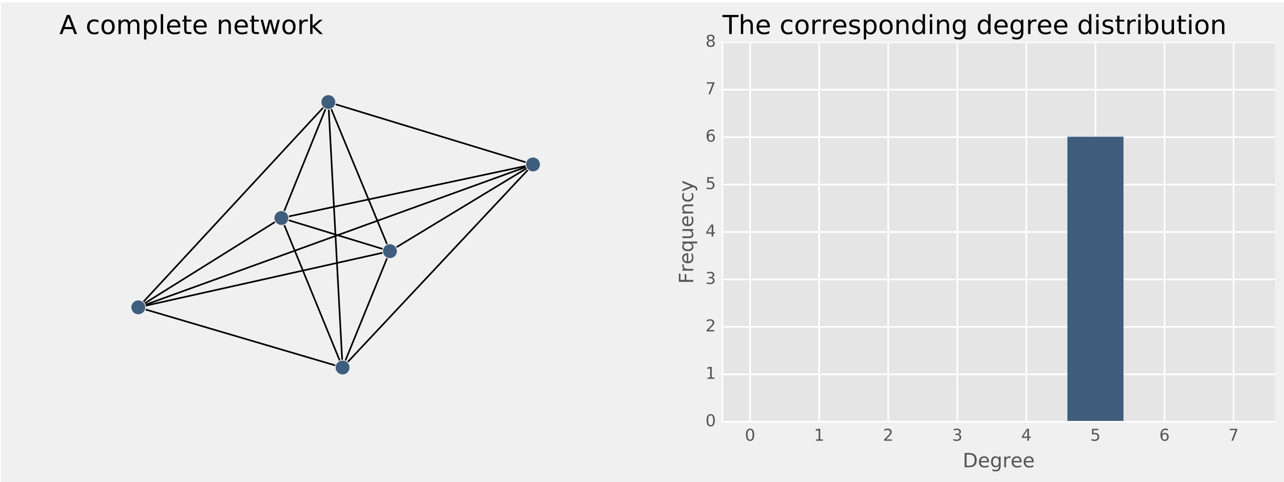
Game theory, also emerging in the 20th century, is another mathematical pillar of modern network theory. It is concerned with strategic interactions of rational players and develops models that allow predicting – under very restrictive idealized conditions – the behavior of the sequentially interacting players in the game. The development of game theory entailed the possibility of models of games on networks.[7] Another closely related strand of game-theoretical literature focuses on the formation of networks [Jackson, 2003, Goyal, 2007]. The

[6] Or, more precisely, he proved that a graph has a path containing every edge exactly once exists if and only if the graph is connected and has exactly zero or two nodes with an odd degree.

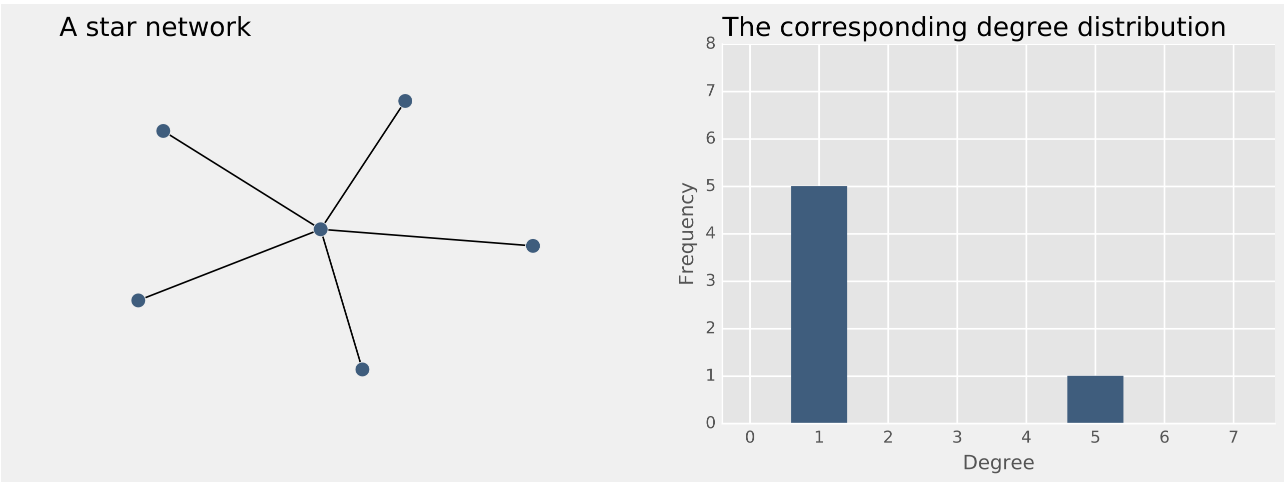
[7] An excellent overview and synthesis of such models is given in Jackson and Zenou [Jackson and Zenou, 2015].

Term	Mathematical formulation	Explanation
Graph	$\mathcal{G}(V, E)$	A set of vertices and edges.
Vertex	$v \in V$	An element of the graph, e.g. a firm or an individual.
Edge	$e \in V \times V$	A connection between two vertices.
Degree	$\delta(v)$	The number of edges connected to a vertex v.
Walk	$W(v_0, v_k)$	A sequence of vertices and edges.
Path	$P(v_0, v_k)$	A path is a walk where all vertices and edges are distinct. The length of P is defined as the number of edges contained in P.
Distance	$d(v_0, v_k)$	The length of the shortest path between v_0 and v_k. If there is no path between v_0 and v_k, then $d(v_0, v_k) = \infty$.
Diameter	$diam(\mathcal{G}) = \max\{d(v_i, v_j) \vert v_i, v_j \in V\}$	The longest shortest path between any two vertices in $\mathcal{G}$.
Connectivity		A graph $\mathcal{G}$ is connected if there exists a path between every pair of distinct vertices.
Clustering	$\mathcal{T}(\mathcal{G}) = \frac{\#\text{triangles}}{\#\text{triads}}$.	A triangle is a set of three different vertices that are all connected to each other. A triad is a set of two edges and one shared vertex.

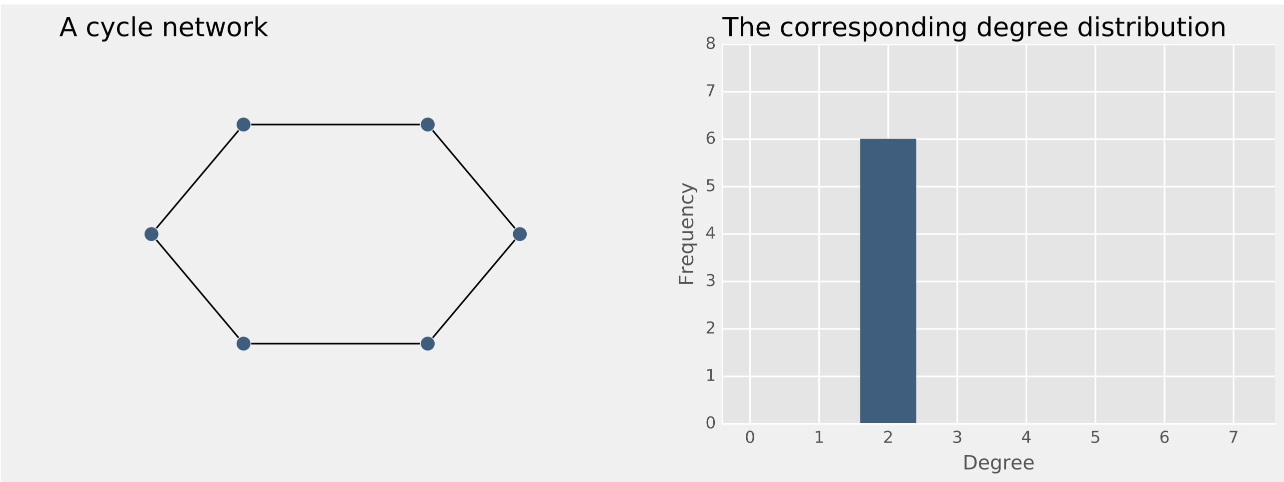
Table 1: Some basic graph theoretic terminology. For an in-depth introduction see e.g. [van Steen, 2010]



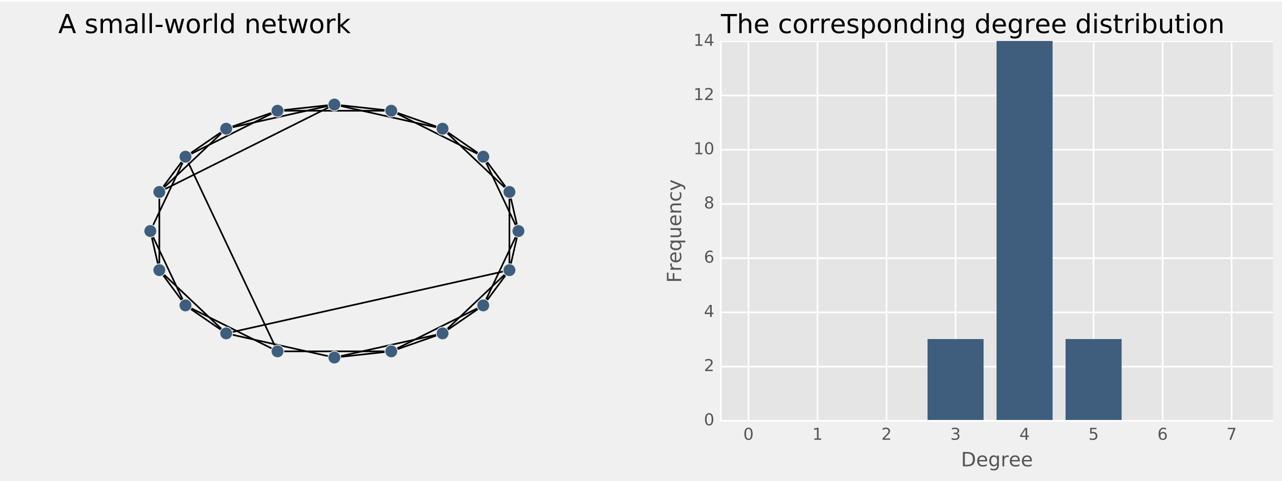
(a) A complete network and its corresponding degree distribution: all agents are connected to each other and consequently have the same degree.



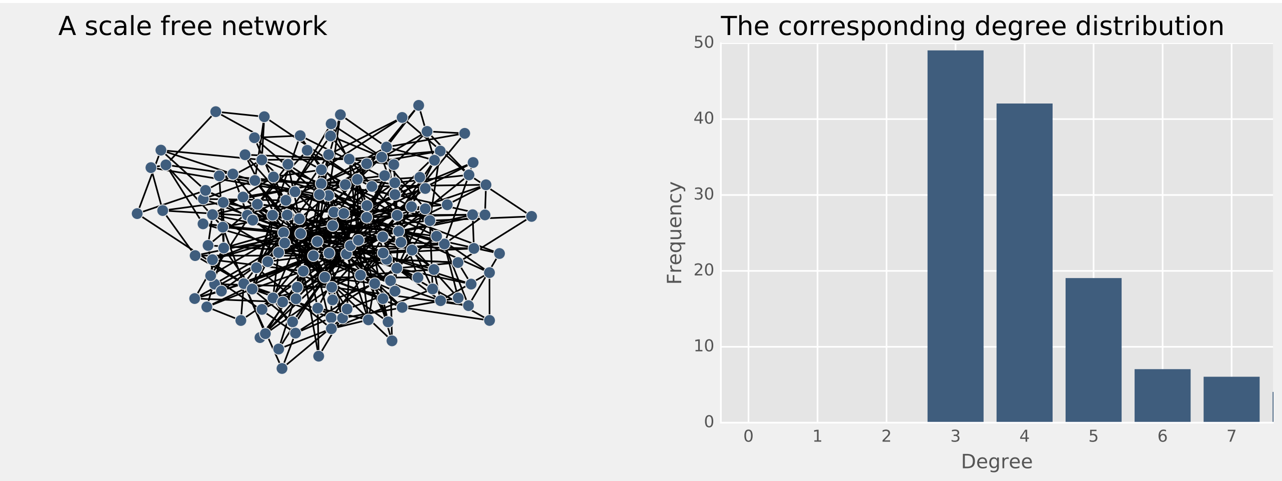
(b) A star network and its corresponding degree distribution: one central agent is connected to every other agent.



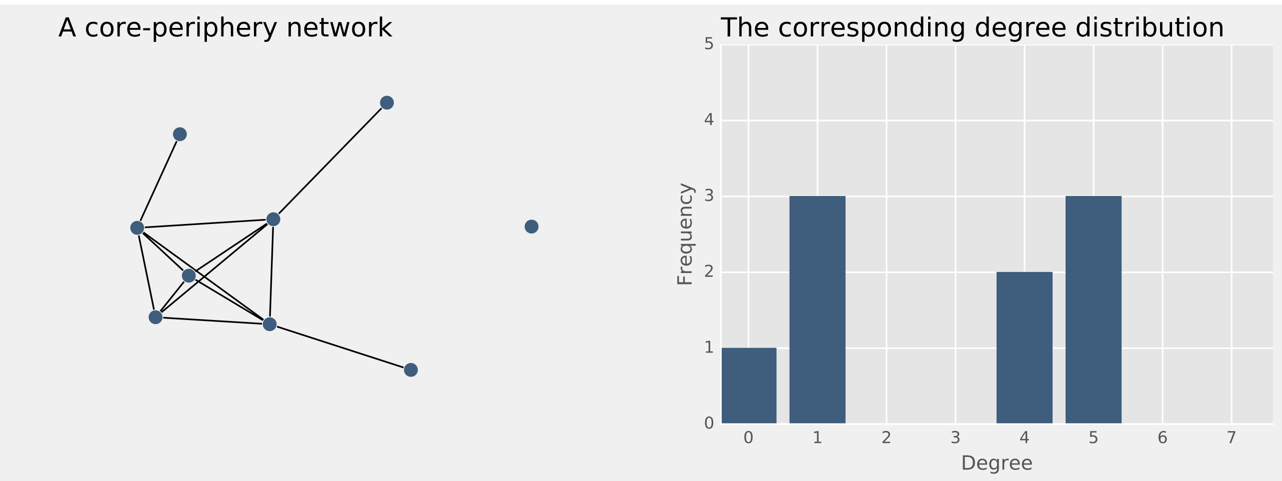
(c) A cycle network and its corresponding degree distribution: every node is connected to his two neighbors.



(d) A small world network and its corresponding degree distribution. More important than the degree distribution is the fact that this network has a small diameter and high clustering.



(e) A scale-free network and its corresponding degree distribution: there are very few well-connected agents with high degrees and many agents with low degrees. The degree distribution is heavy tailed and follows a power law.



(f) A core-periphery network and its corresponding degree distribution: a central cluster of agents is very well connected. The peripheral agents are connected only to the core of the network.

Figure 1: Some idealized forms of networks and their corresponding degree distributions.

concepts and models from these two fields turned out to provide a rich theoretical basis for numerical agent-based simulation modeling which is another powerful tool to study networks, particularly dynamics of formation and development of networks of higher complexity under less restrictive assumptions.

2.1.2 Networks in economic theory

From today's point of view, it may seem obvious that economic systems are always built on a social layer of many interacting entities (agents, firms, and others) and that the microstructure of these systems matters in various ways for their nature as a whole. But this has not always been the case. Much of traditional economic theory derives from concepts such as mechanical equilibria in a price-utility system (which effectively eliminate any importance of the micro-level structure) or the representative agent (which justifies the treatment of micro- and macro-layer as identical and homogeneous).

Network theory entered economics – well after the fixation of the Walrasian-Marshallian microeconomic standard – via the study of nonlinear interactions of aggregate concepts such as industries in supply relationships. These interdisciplinary approaches, e.g. [Goodwin, 1947, Simon, 1953] were soon joined by other traditions of literature that investigated the role of social networks in economics and of different network structures at the micro-layer of economic interactions between firms and agents of all kind (e.g. [Bowles and Gintis, 1975] following advances in sociology, see section 2.1.3). This enabled agent-based models which, based on earlier Schumpeterian and institutionalist groundwork, were very successful in describing industry dynamics realistically (see, e.g. [Nelson and Winter, 1982, Arthur, 1989]).

However, the fact that earlier theories did not take network theory into account does not mean that the respective models are not subject to properties resulting from their implicitly assumed underlying network. General equilibrium theory, for example, presumes in effect either star networks (with a hypothetical auctionator in the center position, see Figure 1b) or complete graphs - which result from the assumption of perfect homogenity in a hypothetical global market without transaction costs or any institutional obstacles (see Figure 1a). Naturally, not all economists were content with this theory. Institutionalists criticized the lack of representation of human social reality. Veblen [Veblen, 1898] ridiculed the concept of human nature employed in (in this case Carl Menger's) equilibrium theory as "hedonistic man"; Polanyi [Polanyi, 1944] argued that the economy was not only embedded in social relations but that the project of equilibrium theory was to disentangle this - something he argued to be absurd and impossible. Both Veblen and Polanyi understood that socio-economic systems comprise of and give rise to more complex network structures but the tools to apply this to formal models were not available at the time both in terms of theoretical concepts and in terms of computation power.

2.1.3 Sociological contributions to network research

The common ground of social network theorizing is the notion that individuals are embedded in social structures. The explanation of causes and consequences of various types of interrelations among individuals is one of the key topics in social science.

Simmel [Simmel, 1922] already emphasized the fact that the nature of ties among individuals affects their behaviors in multiple ways. In the mid of the 20^{th} century, sociologists started to employ graph theoretical concepts to operationalize social structures. One of the pioneers in this research area was Barnes [Barnes, 1954] who helped coin the term “social network”. The concept attracted a great deal of attention and constituted the starting point for new research in the field. Several important advances in the theory of social networks date back to this period. For instance, Milgram’s [Milgram, 1967] letter-passing experiment showed that people in the United States are separated by, on avarage, only six degrees of separation. That is, the average shortest path between any two individuals[8] is no longer than six interaction steps. The findings and implications triggered countless research efforts on ”small-world characteristics” in subsequent years (for an overview, see: [Uzzi et al., 2007] and Section 3).

The social capital and embeddedness literature [Laumann et al., 1978] emphasizes that economic actions and outcomes are influenced by the context in which they occur. A controversial discussion in social capital literature arose on whether and to what extent weak ties [Granovetter, 1973, Levin and Cross, 2004] or strong ties [Uzzi, 1996, Krackhardt, 1992] affect the actors’ behavior and outcomes in social and economic networks.[9] Other seminal contributions [Bourdieu, 1986] paved the way for what we refer to as “closure” theory [Coleman, 1988]. The concept is based on the notion that a network actor’s positioning in a “cohesive” network structure, densely interconnected and interdependent agents at least at the local level, goes along with several advantages. Cohesion is typically assumed to facilitate “the build-up of reputation, trust, social norms, and social control, for example by coalition building to constrain actions, which facilitates collaboration” [Nooteboom, 2008, p.619].

By contrast, the structural hole theory [Burt, 1992] put forward an efficiency argument and assumes that a network position to be beneficial when it allows the actor to bridge the gap between two unconnected (or at least less connected) subgroups of the network. Integrative approaches between these two theoretical concepts emerged recently [Burt, 2005, Rowley et al., 2000].

2.2 What are inter-firm networks and why do they exist?

In the late 20^{th} century a controversial debate among sociologists and economists arose on the very nature of hybrid organizational forms. Why do individual economic entities develop decentralized cooperative practices and do not limit their innovative activities to the hierarchies within the firm or exchange their results on the market (if there were such a thing as an ideal free market)?

The common ground of traditional economic explanations of hybrid organizational forms is the use of transaction cost arguments. In this context, economists [Ouchi, 1980, Jarillo, 1988, Williamson, 1991] have argued that hybrids are an organizational form positioned intermediately between markets and hierarchies. According to [Williamson, 1991], the key distinguishing feature of hybrids compared to other forms of governance is a flex-

[8] The implicit network model in this context is that vertices stand for individuals and edges indicate direct acquaintance or interaction.

[9] Granovetter’s [Granovetter, 1973] concept of weak and strong ties was designed to capture the overlap between connected agent’s direct neighborhood with the strength of the link higher the larger the overlap while weak ties tend to be links to more distant parts of the network.

ible contracting mechanism that facilitates continuity and efficient adaptation [Nee, 1992, p.2]. He conducted a discrete structural analysis in order to compare the three supposed generic forms of economic organization – markets, hybrids and hierarchies – in terms of governance cost efficiency with regard to the level of uncertainty, frequency of disturbance, and asset specificity. One of the key findings from this comparative-static analysis is that transactions characterized by an intermediate level of asset specificity are most efficiently processed by hybrid organizational forms, i.e. innovation networks [Williamson, 1991, p.284].

Many institutionalists, however, reject the argument since boundedly rational agents acting under true uncertainty are neither able nor willing to perform these transaction cost calculations [Hodgson, 1993]. An evolutionary argument could be applied (i.e., that they do not optimize their organizational type but evolutionary selection works in its favor and eliminates other types), but this argument fails to recognize that there is a huge number of environmental and institutional factors beyond transaction costs that would interfere with such a selection mechanism.

Sociologists proposed an alternative explanation for the existence of hybrid organizational forms. They argued that hybrids have to be seen as unique organizational structures and thus should be considered an organizational form in their own right [Powell, 1987, Podolny and Page, 1998]. According to this line of argument, the transaction cost perspective fails to see and explain the enormous variety of forms that cooperative arrangements can take. Powell [Powell, 1987, p.77-82] draws up four factors that explain the emergence, existence and proliferation of hybrid organizational forms: (I) hybrid organizational forms allow greater flexibility and adaptability to rapidly changing environments (II) hybrids allow large organizations, which are usually considered to be structurally inert and thus resistant to change, to overcome, at least to some extent, these limitations; (III) hybrids provide fast and flexible access to information and knowledge located outside the firm's boundaries; (IV) hybrids have to be understood as a variant or application of the "generalized reciprocity concept" (i.e. individual units do not exist in isolation but rather in relation to other units, cf. Podolny and Page [Podolny and Page, 1998]) that creates legitimacy, reputation and mutual trust, and thus generates an efficient and reliable environment for exchange and transfer of information.

The preceding discussion provides very different perspectives on the same phenomenon - i.e. the explanation of the very nature of hybrid organizational forms such as economic networks. The transaction cost logic does certainly not capture the multiplicity and complexity of economic network observable in real life; the explanation of the existence of economic networks cannot be reduced to a transaction cost optimization problem. This is in line with institutional and evolutionary arguments on the role of uncertainty and bounded rationality in market processes. The sociological view on networks also represents a contradiction to the transaction cost perspective. The explanation of the very nature of networks is based on a more comprehensive understanding. It incorporates several important aspects which are inherently entailed in institutional and evolutionary lines of argument.

3 The structure and dynamics of socio-economic networks

Much of conventional modeling implicitly assumes trivial networks: general equilibrium theory, for example, usually assumes star networks (i.e. one central auctioneer mediating the trades between the other agents, see Figure 1b), or evolutionary game theory usually assumes complete networks (i.e. a relational structure in which everyone interacts with everyone else with the same probability, see Figure 1a). One reason for this may by that before the great advances of network theory in the 1990s, networks were usually not considered an important feature of a model in economics. But today we know that most real-world networks are described well by neither star nor complete networks and that this has important consequences. As a result, the well-established practice in mainstream economics is far too limited.

Section 3.1 offers an overview of the most fundamental stylized facts of real-world networks. Examples for studies that identify and explain these regularities are summarized in an online appendix to this article. Section 3.2 discusses dynamics on and of networks in more detail. For examples and applications to problems in economics, see the online appendix.

3.1 Some stylized facts of economic networks

We focus on empirical results regarding the degree of clustering in economic networks, their diameter and their degree distribution mainly for two reasons. Firstly, these characteristics received the most attention in explorative studies and empirical results on their regularities are abundant. Secondly, they represent the most distinctive properties of economic networks for which empirical results are available. For convenience, we quickly described all technical concepts used in this section in Table 1 and Figure 1. For a more precise and technical treatment of the concepts you may consult a textbook on network theory, e.g. [van Steen, 2010].

3.1.1 Clustering

A distinctive feature of social (compared to non-social) networks is their high degree of clustering.The precise interpretation of clustering depends on the definition of the edges: for innovation networks, for example, , an edge exists between two vertices if the corresponding firms hold up close research collaboration (no matter how close they are geographically). Clusters are therefore interpreted in a *functional* way. Functional clusters are a common phenomenon, e.g. if one considers cooperation networks among firms [Storper and Harrison, 1991]. Here, clusters are of particular theoretical interest as they tend to “outgrow” the market: close relations among the different players may be initiated for economic reasons, but after some time reciprocal relationships yield a higher level of trust. This may be one reason for the stability of industrial clusters.

But there are many other instances where clusters were identified in economic networks, e.g. countries in the world trade networks form clusters of dense trade relationships with each other [Fagiolo et al., 2010], or banks in financial markets form clusters of mutual lending and borrowing [Fricke and Lux, 2014].

In all these cases, the identification of clusters represented a vantage point for more concise models of the phenomenon under study in which the emergence of the cluster, and its economic importance could be considered.[10]

3.1.2 Small-World property

Social networks are not only highly clustered, they are also characterized by short average path lengths.

Networks that combine these two properties, strong clustering and small diameter, are referred to as *small world networks* (see Figure 1d).[11] It has been an important *empirical* contribution to show that small-world networks are common in the economy and to motivate the *theoretical* question of how these networks emerged and what their consequences are. Are there common mechanisms causing the network to be so similar in so different areas? Studies providing potential answers to this questions are summarized in the online appendix to this article.

Empirical exercises addressing the structure of knowledge transfer networks among firms [Cowan and Jonard, 2004], firm ownership [Kogut and Walker, 2001], relations among the boards of directors of the biggest US firms [Davis et al., 2003], the collaboration among research institutes [Cowan and Jonard, 2004], and firm's research collaborations [Phelps and Schilling, 2005]. The readers who want to get a good overview over studies that investigated small-world structures in economics can have a look at the online appendix where we give a concise overview over the respective studies..

3.1.3 Heavy tails and scaling

As in the case of clustering and diameter, the distribution of degrees in real world networks shows a surprising regularity: the degree distribution is highly asymmetric with the number of neighbors (the degree) being inversely proportional to the relative frequency of vertices with this number of neighbors. The resulting distribution is called scale-free, so called as the shape of the distribution remains unchanged no matter which part of the distribution is considered or whether the network is scaled to some level of aggregation (see figure 1e). Such information on how degrees are distributed among the different vertices is important because it may hint at important socio-economic mechanisms operating in the system under study.

Research into network structures of inter-firm networks and other networks in economic systems found that these networks also were scale-free (e.g., [Kim et al., 2002, Souma et al., 2003, Foster, 2005]). The high probability of tail events in such distributions is particularly relevant because averaging over large numbers of observations may not work since the central limit theorem may not be applicable. Risk management relying on such averaging operations would consequently fail. This is particularly problematic in corporate ownership and corporate lending networks which have indeed been found to be heavy tailed [Iori et al., 2008, Battiston et al., 2007].[12]

[10] The online appendix (page 1) reviews four examples of analyses of spatial and non-spacial clusters in economics.

[11] The name stems from Milgram's [Milgram, 1967] famous study according to which every person on the planet knows any other person with on average only six intermediate steps.

[12] The identification of scaling laws is not limited to economic networks but was motivated by findings in several other fields (stock price returns, firm sizes, city sizes, etc., see e.g. Newman, [Newman, 2003]).

It should be noted that some doubt has been cast in recent years on whether all distributions claimed to be scale-free actually belong into that category. It is difficult to statistically differentiate between scale-free (power law) distributions and other candidates including log-normal, exponential with cutoff and less regular distributions [Clauset et al., 2009, Heinrich, 2014]. The property of heavy tails, however, remains unaffected and some or all of the implications may also be preserved for these alternative distributions. [Schweitzer et al., 2009] give an overview over more recent empirical findings and the more recent discussion of heavy tails in economic networks.[13]

3.1.4 Core-Periphery structure

Many relevant economic networks – such as lending networks among banks and trade networks among countries – can more precisely be characterized as core-periphery network.

In its most basic sense, the core-periphery concept is based on the notion of "(...) a dense, cohesive core and a sparse, unconnected periphery" [Borgatti and Everett, 2000a]. This means that in a core periphery network basically two types of vertices exist: one group of vertices that are very closely connected (the "core"), and another group of vertices (the "periphery") that are sparely connected and typically spread across several small and unconnected components (see figure 1f).

Hence, the core of the network occupies a dominant position in contrast to the subordinated network periphery and the identification of core-periphery structures in real world networks may help identifying important differences in power among different actors in a network. Rank and her colleagues [Rank et al., 2006], for instance, have argued that actors in the core of a network have a favorable position for negotiating with peripheral actors in bargaining networks.

Concrete empirical strategies to identify core-periphery patterns were proposed by [Borgatti & Everett, 1999] and [Holme, 2005] (the latter based on the well known k-core concept of [Doreian and Woodard, 1994]). And indeed, building on the seminal contributions of Craig and von Peter [Craig and Von Peter, 2010], economists found, for example, that the lending behavior of banks can be much more adequately described by core periphery networks than by scale-free networks [Fricke and Lux, 2014].

This empirical finding does not only have descriptive value, it also helps identifying the generative mechanisms that bring about such networks of lending and to study potential outcomes of policy measures in this context. In banking networks, core and periphery elements play different roles in the financial system that should be taken into account for a reasonable regulation to be implemented.

But core-periphery networks can also be found in very different contexts, such as the German laser industry sector[Kudic et al., 2015], and supply chains in general [Bair, 2008] and international trade networks [Fagiolo et al., 2010].[14] In international trade, some countries form a center of the trade network and other countries are connected only to a few of these central vertices, thus being strongly dependent on them. The identified pattern is very stable over time, including time spans of increasing globalization [Fagiolo et al., 2010].

[13] The online appendix (page 3) reviews theoretical and empirical analyses of scaling networks.

[14] For further examples, see the online appendix (page 4).

It should be considered e.g. in the discussion about the socio-economic consequences of globalization, a prominent topic in the evolutionary-institutional community: the marginalization of certain countries in such a trade network both polarizes wealth and capabilities of different countries and does not contribute to overall efficiency [Fagiolo et al., 2010].

Note that the three stylized facts we have introduced all capture different aspects of networks and are complementary insights, rather than contradictory: a network can be heavy-tailed, feature many clusters, and have a core-periphery structure. The various measures tell us different things about the networks, all of which are important if one is willing to identify the mechanisms having caused these striking regularities.

3.2 Understanding the dynamics on networks

The topology of networks is fundamentally important in economic contexts because the structure of a firm's (or an agent's) environment determines to a large part the risks it has to confront as well as its strategic options and its potential to use them. It is therefore crucial to understand why there are so many stable regularities of the social networks we considered so far.

To answer this question one should pay particular attention on what happens on the networks: the development of such networks tends to depend on both the decisions of the firm or agent representing the vertices and their success in surviving immediate threats both alone and in conjunction with their local environment. Less successful parts of the network will be more volatile or may fail completely and can (in cases in which persistent regularities emerge) lead to an evolution-like self-organization of the network as a whole. It is obvious that structure and function of properties of the network are interlocked in this case and will co-evolve. This structure-function relationship is one of the research frontiers of modern network science but it is not likely that much insight can be gained without a reference to socio-economic theory: it is our hope that once socio-economists engage themselves with such network-theoretic questions, they may be able to contribute the missing theoretical mechanisms that make sense of the observed regularities.

One natural approach to model strategic interaction on networks so far is to study games played on graphs. For simple networks, analytical results on how the structure of networks affects the outcome of games played are available (e.g. [Kets et al., 2011]) but the effect of complex, empirical networks must usually be studied via simulations. [Pacheco et al., 2009] for example study how network structure affects the performance of different strategies in the Prisoners Dilemma. This aligns well with the institutionalist literature on the topic of economic trust and recognized interdependence, and many complementarities are to be exploited.

Various studies analyzed the emergence of an commodity-exchange equilibrium on networks [Albin and Foley, 1992, Gintis, 2007, Axtell, 2005] and the emergence of social classes [Axtell et al., 2001] in bargaining games on networks among other things.

Further, it was found that models from epidemics are well-suited to model information diffusion and technology adoption (adapted from models of the diffusion of epidemics). A distinguishing factor for such models is that diffusion speed depends crucially on the current prevalence of the property in question and the size of the reachable population as well as the properties of the network. Further, the case of technology diffusion likely involves network effects which are quite different from global network effects [Arthur, 1989] which are monopolizing. Local network effects in small-world networks and scale-free networks may, depending on the parameters of the network, allow for either monopolization or for the persistence of niches of minority technologies [Uchida and Shirayama, 2008, Pegoretti et al., 2009].

4 A summary, open questions and fruitful avenues for further research

We put forward the argument that a stronger integration of two research domains - socio-economics and network theory - is the key towards a more comprehensive understanding of the causes and consequences of interactions in complex socio-economic systems. Both approaches share the notion that all economic processes and outcomes are accompanied by interaction among individuals. However, the step from single interactions between two actors towards repeated and more complex interaction patterns bring us directly to the concept of networks, where at least two constitutional features matters: structure and dynamics.

Over the past decades a rich, and to a large extend quantitatively oriented, body of literature has emerged that is very instructive on how networks evolve. It provides the formal language and thus the adequate vocabulary to describe and understand the structure of socio-economic systems from a realist perspective and to identify the structural mechanisms that are driving their dynamics. Today we know that the positioning of actors in a socio-economic system as well as the topology of the system itself affects the performance outcomes of the embedded actor in multiple ways. We also know that these outcomes are highly context-specific and affected by the individuals‘ embeddedness in other spaces, such as regional, institutional, or cultural dimension. Our discussion of the literature throughout this paper shows how a quantitative approach to socio-economic networks can help to formulate more concrete questions about the role played by social structure and to identify empirical regularities in the interaction structure of socio-economic systems.

There are some practical limitations to what can be achieved by quantitative network science. Many of the advanced techniques require a significant amount of data. For example, there is few data on corporate ownership networks, trade, and supply networks. Most of it originates from particular contexts or particular time periods which makes generalization difficult. A similar problem arises for innovation networks. Innovation networks are frequently inferred from co-patenting data. But this practice is subject to well-known limitations. For instance, patent applications do not carry any information about the duration of cooperation among the firms. Consequently, various arbitrary assumptions typically have to be made when working with this type of data. Data on social and professional networks is scarce for reasons of privacy and the difficulty to gather such data. In effect, a large number of networks relevant for economics remains completely unstudied and the question of whether missing data introduces serious biases into the empirical study of social networks (for example because more powerful actors are more likely to conceal undesired data) is important and requires further research.

Another promising avenue for future research concerns the dynamics of networks. Quantitative network science is still in its infancy when it comes to the identification of mechanisms that drive the change of networks over time. Recent research shows that most frequently applied network change mechanisms (e.g. the preferential attachment mechanism) provide, at best, a very limited explanation for the emergence of empirically observable real-world innovation networks [Fricke & Lux, 2016]. A socio-economic perspective could effectively address this gap of understanding in the following ways:

Firstly, a sound theory of individual decision-making is required to understand the dynamics of social networks: socio-economic agents do not mechanistically respond to stimuli from their environment. Socio-economists have developed a rich and interdisciplinary theory of individual decision-making that is firmly rooted in modern evolutionary theory and instinct-habit psychology [Hodgson, 2012, Elsner, 2014]. The application of this theory may be able to both close the gaps that exist in current explanations of network dynamics, individual positioning, and network formation and contribute to our understanding of why the striking empirical regularities in social networks actually exist.

Secondly, socio-economic systems consist of several ontological levels among which both upward and downward effects play a role [Gräbner, 2016]. Social rules, norms and institutions are prototype examples of structures that exist on higher ontological levels and both depend upon and affect the behavior of and the relations among individuals. Therefore, to provide theoretical explanations on the exact role played by these structural particularities for the emergence and evolution of overall network topologies is highly important.

Finally, the consideration of social networks is likely to have important implications for policy design. The task of developing good policy measures involves reasoning about several ontological levels: on the micro level, the structure of individual decision making and interaction among individuals has to be taken into account. Regulation theorists, for example, should consider ownership networks and coalitions among different business actors. It may also be useful to think of policies that directly influence the structures of the micro level, e.g. by strengthening structures that are beneficial to the emergence of trust. The same holds for interactions among meso-level entities, such as firms, organization, or social groups. Finally, the network structure also has a profound impact on the macro-level of socio-economic systems (including systemic properties such herd behavior or systemic risk in financial markets), which may also be considered and targeted by policy measures [Gräbner and Kapeller, 2017].

Socio-economists may contribute to the understanding on all these levels and their interaction. Most importantly, they can highlight the ethical dimension of public policy and provide the corresponding normative elaborations. It is essential that socio-economists are involved in these discussions and do not leave the ground for an allegedly value-free assessment of socio-economic networks and related policy questions. In summary, the two camps of network scientists and socio-economists have much to offer to each other and a more symbiotic relationship between them is warranted: network theorists developed a huge set of tools to model networks and to identify their empirical regularities. Socio-economists produced a tremendous amount of knowledge about socio-economic mechanisms that may help to develop the mechanismic explanations of the structure of the socio-economic systems we see. Only with knowledge of these mechanisms will we be able to significantly enhance our understanding of the complex socio-economic systems we are, at the same time, interested in and to work on effective and ethically justified policies for such systems.

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Approaches to the Modelling of Economic Networks – Online Appendix for Gräbner, Heinrich, and Kudic: Structuration processes in complex dynamic systems

Clustering			
Reference	*Content*	*Methods*	*Main findings*
Schelling, T. C. (1971). Dynamic models of segregation. *Journal of Mathematical Sociology*, 1:143–186.	- Segregation as result from the interplay and dynamics of interactive individual choices - Distribution of members in neighborhoods defined by reference to their own location - Second model deals with compartmented space - Deals also with 'neighborhood tipping'	- One simulation model and one analytic model	- No simple correspondence of individual incentive to collective results - Exaggerated separation and patterning result from the dynamics of movement - Inferences about individual motives cannot be drawn from aggregate patterns
Krugman, P. (1997). How the economy organizes itself in space: A survey of the new economic geography. In Arthur, W. B., Durlauf, S., and Lane, D., editors, *The Economy as an Evolving Complex System II*, pages 339-362.Westview Press, Reading, MA.	- Geography of the economy / spatial economy as self-organizing system characterized by interaction of individual decisions - Evolution of spatial economy and emergence of spatial structure	- Illustration and description of models and major lines of research - Discussion of implication for future work	
Arthur, W. B. (1990). 'Silicon Valley' locational clusters: When do increasing returns imply monopoly? *Mathematical Social Sciences*, 19(3):235-251.	- Increasing returns and dominant markets in the context of industrial location - Model of industry location: when do economies of agglomeration lead to a single dominant location monopolizing the industry?	- Modelling industrial location	i) No upper bound to locational increasing returns due to agglomeration, leads to a clustered dominant location ii) An upper bound can produce a monopoly by certain sequences of firm entry, or can lead to a sharing of industry
Elsner, W. (2014). Social economics and evolutionary institutionalism today. Theoretical components and heterodox convergence in a socio-economic perspective. *Forum for Social Economics*.	- Theoretical and methodological discussion of the constitution of social economics - Elements of evolutionary (Veblenian) institutional economics are considered - Focus on "heterodox" convergence - Explanation real-world forms of market, hierarchies and spatial clusters	- Discussion of theoretical concepts and methodology (complex modeling, game theory, computer simulations)	
Karrer, B. and Newman, M. E. J. (2011). Stochastic blockmodels and community structure in networks. *Phys. Rev. E*, 83:016107.	- Stochastic blockmodels as a tool for detecting community structure in networks - Variation in vertex degree and generalization of blockmodels which leads to an improved objective function for community detection in complex networks	- Generalized blockmodels - Heuristic algorithm using an objective function or its non-degree-corrected counterpart	- Degree-corrected version outperforms the uncorrected one in real-world and synthetic networks

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Small World Property			
Reference	*Content*	*Methods*	*Main findings*
Milgram, S. (1967). The small world problem. *Psychology today*, 2(1):60-67.	- Concept and structure of small world phenomenon - Examination of the average path length for social networks (six degrees of separation)	- Experiments with randomly selected citizens of the United States	- Social networks are small world networks in which in average everyone is six or fewer steps away
Watts, D. J. and Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. *Nature*, 393(6684):440-442	- Characteristics and dynamics of small world networks and connection topology - Neural network of the worm *Caenorhabditis elegans*, the power grid of the western United States, and the collaboration graph of film actors are shown to be small-world networks	- Exploration of simple models of networks with rewiring by introduction of increasing amount of disorder - Generating algorithm for small-world networks	- Small world networks can be highly clustered, like regular lattices, and have small path lengths, like random graphs - Enhanced signal propagation speed, computational power and synchronizability - Infectious diseases spread more easily in small-world networks than in regular lattices
Baum, J. A. C., Calabrese, T., and Silverman, B. S. (2000). Don't go it alone: alliance network composition and startups' performance in Canadian biotechnology. *Strategic Management Journal*, 21(3):267-294.	- Combination of theory and research on alliance networks - Impact of variation in startups' alliance network composition on early performance	- Analysis of Canadian biotech startups' performance with panel data	- Alliance network configuration at the time of founding affect early performance - Enhancement of performance by established alliances, access to information alliances with rivals - Explanation of how and why firm age and size affect firm performance
Uzzi, B. and Spiro, J. (2005). Collaboration and creativity: The small world problem. *American Journal of Sociology*, 111(2):447-504.	- Dynamics of small world networks - Impact of small world properties on performance	- Analysis of the small world network of the creative artists who made Broadway musicals from 1945 to 1989	- Varying "small world" properties of the systemic-level network affects creativity in terms of financial and artistic performance
Fleming, L., Charles King, I., and Juda, A. I. (2007). Small worlds and regional innovation. *Organization Science*, 18(6):938-954.	- Small-world networks in regional context - Investigation of the effects of collaboration networks on innovation	- Development and exploitation of a novel database on patent coauthorship using statistical models	- Existence of regional small-world structures enhance innovative productivity within geographic regions - Shorter path lengths and larger connected components correlate with innovation
Schilling, M. A. and Phelps, C. C. 2007). Interfirm collaboration networks: The impact of large-scale network structure on firm innovation. *Management Science*, 53(7):1113–1126.	- Influence of alliance networks structure on potential knowledge creation / innovation	- Longitudinal study of the patent performance of 1,106 firms in 11 industry-level alliance networks	- Interfirm collaboration networks with short path lengths and which are highly clustered have greater innovative output

Approaches to the Modelling of Economic Networks – Online Appendix for Gräbner, Heinrich, and Kudic: Structuration processes in complex dynamic systems

Heavy Tails and Scaling			
Reference	*Content*	*Methods*	*Main findings*
Price, D. D. S. (1976). A general theory of bibliometric and other cumulative advantage processes. *Journal of the American Society for Information Science*, 27(5):292-306.	- Cumulative Advantage Distribution is proposed which models the situation in which success breeds success	- Modelling Distributions	- Stochastic law is governed by the Beta Function containing only one free parameter which approximated diverse social science phenomena
Barabási, A.-L. and Albert, R. (1999). Emergence of scaling in random networks. *Science*, 286(5439):509- 512.	- Emergence of networks - Property of large, complex networks: vertex connectivities following a scale-free power-law distribution	- Modelling scale-free distributions	- Networks expand continuously by the addition of new vertices - New vertices attach preferentially to sites that are already well connected - Development of large networks is governed by robust self-organizing phenomena
Podolny, J. M. (1994). Market uncertainty and the social character of economic exchange. *Administrative Science Quarterly*, 39(3):458-483.	- Organizations overcome the problems of market uncertainty in selecting exchange partners	- Study of investment banking relationships in the investment grade and non-investment-grade debt markets from 1981 to 1987	- The greater the market uncertainty the more organizations engage in exchanges relations they already have transacted in the past - The greater uncertainty, the more that organizations engage in transactions with those of similar status
Stuart, T. E., Hoang, H., and Hybels, R. C. (1999). Interorganizational endorsements and the performance of entrepreneurial ventures. *Administrative Science Quarterly*, 44(2):315-349.	- Examination of the ecological consequences of initial public offerings (IPOs) and acquisitions - Focus on how the spatial distribution influence the location-specific founding rates of new companies	- Count models of biotechnology firm	- IPOs of organizations located contiguous to or within an MSA (metropolitan statistical area) accelerate the founding rate within that MSA - Acquisitions of biotech firms situated near to or within an MSA accelerate the founding rate within the MSA when acquirer enters from outside of the biotech industry - Enforceability of post-employment non-compete covenants moderate these effects
Vázquez, A. (2003). Growing network with local rules: Preferential attachment, clustering hierarchy, and degree correlations. *Phys. Rev. E*, 67:056104.	- Linear preferential attachment hypothesis as explanation for the existence of networks with power-law degree distributions	- Analytical and numerical results of different local rules	- Effective linear preferential attachment is the natural outcome of growing network models based on local rules - Local models offer an explanation to other properties like the clustering hierarchy and degree correlations
Ghoshal, G., Chi, L., and Barabási, A.-L. (2013). Uncovering the role of elementary processes in network evolution. *Scientific Reports*, 3(2920).	- Identification of elementary mechanism and their role on network evolution - Focus on formation and deletion of connections	- Formulating and solving a model with minimal processes of network evolution	- Contribution to growth by formation of connections between existing pair of vertices, while others capture deletion - Dependence of the removal of a node with its corresponding edges, or the removal of an edge between a pair of vertices

Approaches to the Modelling of Economic Networks – Online Appendix for Gräbner, Heinrich, and Kudic: Structuration processes in complex dynamic systems

Core-Periphery Patterns			
Reference	*Content*	*Methods*	*Main findings*
Karrer, B. and Newman, M. E. J. (2011). Stochastic blockmodels and community structure in networks. *Phys. Rev. E*, 83:016107.	- Stochastic blockmodels as a tool for detecting community structure in networks - Variation in vertex degree and generalization of blockmodels	- Generalized blockmodels - Heuristic algorithm for community detection using an objective function or its non-degree-corrected counterpart	- Improved objective function for community detection - Degree-corrected version outperforms the uncorrected one in the real-world and synthetic networks
Hidalgo, C. A., Klinger, B., Barabási, A.-L., and Hausmann, R. (2007). The product space conditions the development of nations. *Science*, 17(5837):482-487.	- Characteristics and adaption of new products - Network of relatedness between products or "product space" and national technology and income level	- Empirical methods	- More-sophisticated products are located in a densely connected core - Less-sophisticated products occupy a less-connected periphery
Holme, P. (2005). Core-periphery organization of complex networks. *Phys. Rev. E,* 72:046111	- Measurement of the core-periphery dichotomy for a number of real-world and model networks - Focus on statistical properties of the core and of the *n* neighbors of the core vertices for increasing *n*	- A coefficient for the measurement of the core-periphery dichotomy is proposed	- Geographically embedded transportation networks have a strong core-periphery structure - Almost all networks have many edges within n neighborhoods at a certain distance from the core
Doreian, P. and Woodard, K. L. (1994). Defining and locating cores and boundaries of social networks. *Social Networks* 16:276-293.	- General procedure for locating the boundary of a network and for discerning the boundaries within a network - First: Expanding (snowball) selection procedure - Second: specification of two critical parameters: the value of *k* for a *k*-core and the threshold, *w*, for the quantitative magnitude of network ties	- Single sector and multi-sector social service inter-agency networks are used	- Method for locating cores and boundaries generates a sequence of nested cores as *k* and *w* are systematically changed
Borgatti, S. P. and Everett, M. G. (1999). Models of core/periphery structures. *Social Networks* 21:375-395.	- Concept and formalization of a core/periphery structure - algorithm for the detection of a dense, cohesive core and a sparse, unconnected periphery	- Statistical tests for testing a priori hypotheses	- Different models are presented for different kinds of graphs (directed and indirected, valued and nonvalued)
Silva, M. R. D., Ma, H., and Zeng, A. P. (2008). Centrality, network capacity, and modularity as parameters to analyze the core-periphery structure in metabolic networks. *Proceedings of the IEEE*, *96*(8), 1411-1420.	- Deals with genome-scale metabolic networks of organism and their core-periphery modular organization - Focus on hierarchical and modular structure of metabolic networks	Development of method with genome-scale metabolic networks of five representative organisms, which include Aeropyrum pernix, Bacillus subtilis, Escherichia coli, Saccharomyces cerevisiae, and Homo sapiens	- Proposes a parameter: the core coefficient which quantitatively evaluate the core-periphery structure of a metabolic network and which is based on the concepts of closeness centrality of metabolites and network capacity