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Decoding Complexity

Uncovering Patterns in Economic Networks

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Decoding Complexity

Uncovering Patterns in Economic Networks

Doctoral Thesis accepted by
Swiss Federal Institute of Technology (ETH)
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Springer

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Supervisor's Foreword

While globalization seems to have been *the* buzzword since the late twentieth century, scientific insight into the causes and effects, and the benefits and drawbacks of globalization still needs to be fully developed. For an understanding of how globalization works, massive data analysis of economic agents worldwide is an inevitable step. What does the structure of global economic interactions look like? Does it resemble structures found on smaller economic scales, or are there emerging properties on the global level? Do our findings conform to the established economic theories, or must these theories be refined and further developed to cope with these findings? Can we derive models to predict the dynamics in such global networks?

The thesis of James Glattfelder addresses the heart of these scientific questions. Based on the theory of complex networks, it derives a novel approach to investigate large-scale economic networks based on massive analysis of ownership data. It further links these findings to relevant economic questions, such as the measurement of control. For this, James proposes novel ways to quantify economic concepts like "value", "control", "power", and provides computational algorithms to extract these from weighted, directed network structures hidden in large-scale datasets.

A particular highlight of the thesis is the unfolding of a global ownership network of transnational companies (TNC), including their shareholders and their subsidiaries. This analysis identified a rather small, but fully connected core of the network which contains less than 1 % of all nodes, but almost 20 % of the operating revenue of all TNC. This "core" is mostly dominated by financial intermediaries based in the US and UK. The existence of such a structure is an important clue toward understanding systemic risk in economic systems, in particular if seen together with the very strong concentration of control that James has identified. The "emerging picture" reveals the role of a "super-entity" in the global network of TNC, a finding that goes beyond our current knowledge about globalization. The insights obtained in this work even challenge established economic theories, because they are hardly predicted or explained by these.

The content of the thesis is highly original and makes a fundamental contribution to our knowledge of global economic networks. Moreover, it is one of the rare cases where scientific results have made it to the front page of major newspapers and magazines around the world. It thereby fuelled the discussion on inequality, the role of financial institutions, and the control of economic power. I am pleased that the publication of this thesis makes such important findings available to a larger audience.

Zurich, July 2012 Prof. Dr. Dr. Frank Schweitzer

Acknowledgments

When I first embarked on the journey of writing this thesis, originally called "Ownership Networks and Corporate Control: Mapping Economic Power in a Globalized World", I would never have imagined being so lucky. I was able to profit greatly while interacting with a kind group of dedicated people. The continued international media coverage of our work revealed to me that the topic we chose to study is indeed of greater interest and relevance to our society. Surprisingly, there has been little advancement in this direction to understand the interconnected nature of our economic systems and decode the apparent complexity. Finally, I would like to thank the people at *Springer* for accepting the nomination of this work and publishing it in their *Springer Theses* series.

Zurich, June 2012 James B. Glattfelder

Within a few months of writing these words, my 38th birthday will be coming up. As this is an unusually old age for finishing ones thesis, I would like to mention all the people who contributed to the meandering path leading to this milestone. In chronological order: I would like to thank my mother and late father, Caroline and Tazi Glattfelder, who, from an early age on, fostered my budding interest in science. My special gratitude goes out to Peter Henley-Smith from Forest School, London, who coincidentally and spontaneously offered to introduce me to chemistry and physics at the age of 15 and awakened my dormant passion for science.

I thank my employer since 2002, Richard B. Olsen of Olsen Ltd., Zurich, who, from the very beginning on, was highly supportive of my endeavor to complete a Ph.D. and arranged for me to continue working at the company on a part-time basis. I am very grateful to Frank Schweitzer, who was willing to embark on the adventure of advising an older than average and only part-time employed Ph.D. student. I also thank him for his scientific guidance and support.

I am particularly indebted to Stefano Battiston for his continuous and invaluable advice and dedicated tutoring, allowing me to benefit greatly. Moreover, I would like to thank the lively team at the Chair of Systems Design for their friendship and scientific interaction. In particular, Stefania Vitali for a successful collaboration. Finally, I would like to thank Guido Caldarelli for kindly offering to be an ideal co-examiner.

Furthermore, and in general, I am grateful to all my friends who helped and supported me during this undertaking. Last but not least, I am sincerely thankful to Ladina Plattner for being a constant source of joy.

Zurich, June 2010 James B. Glattfelder

Contents

Acronyms

BFS	Breadth-first search (search algorithm)
B-index	Banzhaf index
CC	(Weakly) Connected component
CDF	Cumulative distribution function
COMM	Community (e.g., COMM.1 refers to the largest community)
DRG	Directed random graph
FS	Financial sector
GPAM	Generalized preferential attachment model
H-index	Herfindahl index
IN	In-section of a bow-tie
LCC	Largest CC
LM	Linear model (for estimating control from ownership see also RM and TM)
NACE	(Industry standard classification system)
OCC	Other connected components (everything outside the LCC)
OECD	Organization for Economic Co-operation and Development
OR	Operating revenue
OUT	Out-section of a bow-tie
PC	Participated company
PDF	Probability density function
RM	Relative model (for estimating control from ownership see also LM and TM)
SCC	Strongly connected component (in the main text, this is synonymous with the core of the bow-tie in the LCC)
SH	Shareholder (economic actors holding shares in TNCs)
SS-index	Shapley–Shubik index
TM	Threshold model (for estimating control from ownership see also LM and RM
TNC	Transnational corporation (OECD definition)
TPH	Top power-holder (list of TNCs and SHs that together hold 80 % of the network control)

T&T	Tubes and tendrils (sections in a bow-tie that either connect IN and OUT, are outgoing from IN, or in-going to OUT, respectively)
WWW	World Wide Web

In addition, countries are abbreviated by their two letter ISO 3166-1 alpha-2 codes, e.g., CH, JP, US. etc.

Chapter 1
Introduction

> *We spend billions of dollars trying to understand the origins of the universe, while we still don't understand the conditions for a stable society, a functioning economy, or peace.*
>
> (D. Helbing quoted in Cho 2009)

It sounds paradoxical, but today it appears that we understand more about the universe than our society. We have created systems, that have outgrown our capacity to genuinely understand and control them. In order to try and provide a contribution to the understanding of socio-economic systems, this thesis aims at answering the following questions:

How is economic control distributed globally?
Who are the key economic actors holding the largest fraction of control?
To what degree are the top economic actors interconnected with each other?

The answers to these questions lie at the interface between the realms of social and systems science—namely, economics and the study of complex networks. These two notions are embodied in the main object of study, introduced in Sect. 1.1.3: the ownership network.

In order to understand all the involved issues and concepts, this chapter introduces the related prerequisites. Before the economics topics from the fields of corporate governance and corporate finance are discussed in Sect. 1.2, some general questions need to be addressed:

What are real-world complex networks and how do they relate to the study of complex systems?

The long answer to these questions deals not only with the philosophy of science, discussed in Appendix A.1, but also relates to the two realms of reality that have been successfully understood using formal models: fundamental and complex processes, presented in Sects. A.2.2 and A.2.3 (in general, Appendix A reflects the author's views on these issues and is an attempt to illustrate and illuminate these intangible notions). The short answer is given in the next section.

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1.1 Complex Networks

A *complex system* is usually understood as being comprised of many interacting or interconnected parts. A characteristic feature of such systems is that the whole often exhibits properties not obvious from the properties of the individual parts. This is called *emergence*. In other words, a key issue is how the macro behavior emerges from the interactions of the system's elements at the micro level.

The empirical analysis of real-world complex systems has revealed unsuspected regularities, such as scaling laws, which are robust across many domains (Mantegna and Stanley 1995; West et al. 1997; Amaral et al. 1998; Albert et al. 1999; Pastor-Satorras et al. 2001; Newman et al. 2002; Garlaschelli et al. 2003; Newman 2005; Glattfelder et al. 2011). For more details see Appendix C. This has suggested that universal or at least generic mechanisms are at work in the structure-formation and evolution of many such systems. Tools and concepts from statistical physics have been crucial for the achievement of these findings (Dorogovtsev and Mendes 2003; Caldarelli 2007).

Complex systems are usually very reluctant to be cast into closed-form analytical expressions. This means that it is generally hard to derive mathematical quantities describing the properties and dynamics of the system under study.

Complex systems can, however, be easily described by their structure of interactions. The complexity of the agents that make up the system can be ignored. Therefore any real-world complex system finds its natural formal representation in a graph: the nodes represent the agents and the links their interactions. In essence, the properties of the complex system can be understood by mapping it onto a complex network and then studying the network regularities. This is very much in the spirit of the paradigm, that simple rules give rise to complex behavior. For more details on these issues, see Appendix A.2.3.

Today, complex networks are ubiquitous[1]: phenomena in

- the physical world, e.g.,
  - computer-related systems (Albert et al. 1999; Barabási et al. 2000; Tadić 2001; Pastor-Satorras et al. 2001; Capocci et al. 2006),
  - various transportation structures (Banavar et al. 1999; Guimera et al. 2005; Kühnert et al. 2006),
  - power grids (Albert et al. 2004),
  - spontaneous synchronization of systems (Gómez-Gardenes et al. 2007),
- biological systems, e.g.,
  - neural patterns (Ripley 2008),

[1] For instance, (Strogatz 2001; Albert and Barabási 2002; Dorogovtsev and Mendes 2002, 2003; Newman 2003; Newman et al. 2006; Caldarelli 2007).

  - epidemiology (Meyers et al. 2005),
  - food chains (Garlaschelli et al. 2003; McKane and Drossel 2005),
  - gene regulation (Bennett et al. 2008),
  - spontaneous synchronization in biological systems (Gonze et al. 2005),

- social[2] and economic realms, e.g.,

  - diffusion of innovation (Schilling and Phelps 2007; König et al. 2009),
  - trust-based interactions (Walter et al. 2008),
  - various collaborations (Newman 2001a,b),
  - social affiliation (Brown et al. 2007),
  - trade relations (Serrano and Boguñá 2003; Garlaschelli and Loffredo 2004a,b; Reichardt and White 2007; Fagiolo et al. 2008, 2009),
  - shared board directors (Strogatz 2001; Battiston and Catanzaro 2004),
  - similarity of products (Hidalgo et al. 2007),
  - credit relations (Boss et al. 2004; Iori et al. 2008),
  - price correlation (Bonanno et al. 2003; Onnela et al. 2003),
  - ownership networks (Glattfelder and Battiston 2009; Vitali et al. 2011).

are best understood if characterized as networks. The explosion of this field of research was and is driven by the increasing availability of huge amounts of data, pouring in from neurobiology, genomics, ecology, finance and the World-Wide Web, etc., in combination with the access to massive computing power and vast storage facilities.

1.1.1 Three Levels of Network Analysis

In the last years, in order to offer useful insights into more detailed research questions, several studies have started taking into account the specific meaning of the nodes and links in the various domains the real-world networks pertain to. The study of real-world complex networks can be performed at three levels of analysis. Level 1 is the purely topological approach (best epitomized by a binary adjacency matrix (see Appendix B.2) where links simply exists or don't). Allowing the links to carry information, i.e., have directions and weights, defines Level 2 (Newman 2004; Barrat et al. 2004; Barthelemy et al. 2004; Onnela et al. 2005; Ahnert et al. 2007).

At the highest level of detail, the nodes themselves are assigned a degree of freedom, in the guise of non-topological state variables that shape the topology of the network (Garlaschelli and Loffredo 2004c; Garlaschelli et al. 2005; De Masi et al. 2006). These variables are sometimes also called fitness. See Fig. 1.1 for a visualization of the 3-level approach to complex networks. However, Level 3 type analysis have

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[2] A general reference is Vega-Redondo (2007).

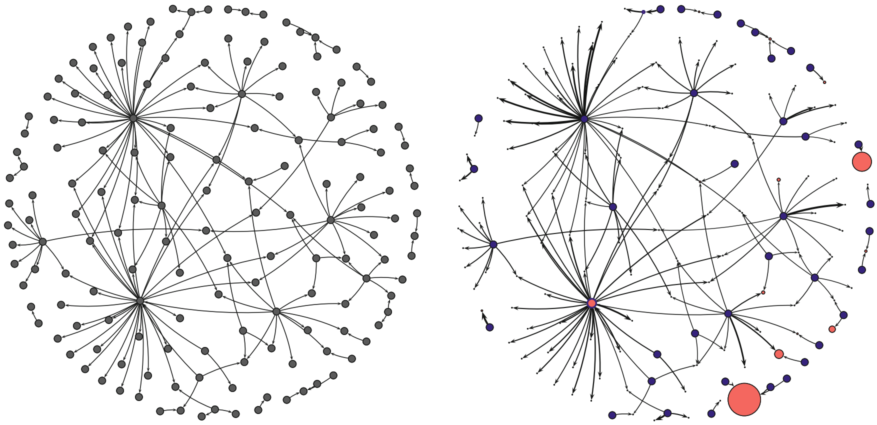

Fig. 1.1 Visualization examples of the same underlying network: (*left*) a directed layout; (*right*) the full-fledged 3-level layout, where the thickness of the links represents their weight and the nodes are scaled by some non-topological state variable; the colors can reflect some additional attribute of the nodes; the graph layouts are based on Geipel (2007)

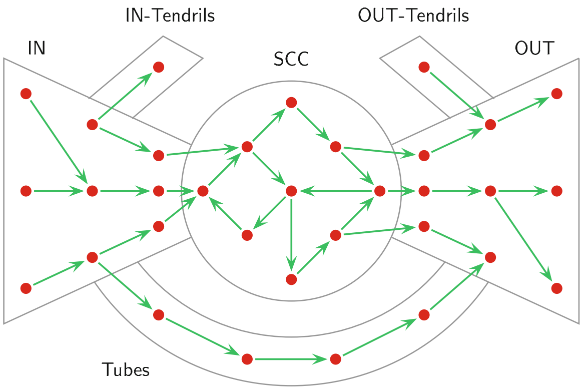

Fig. 1.2 Schematic illustration of a bow-tie topology: the central area is the strongly connected component (SCC), where there is a path from each node to every other node, and the *left* (IN) and *right* (OUT) sections contain the incoming and outgoing nodes, respectively; the set of nodes directly linking the IN and OUT are called tubes; the IN can have outgoing tendrils, and the OUT incoming ones; the tubes and tendrils are referred to as T&T

still today not become state-of-the-art (Caldarelli et al. 2002; Servedio et al. 2004; Garlaschelli and Loffredo 2004b). One reason for this is that considering all three levels of detail does not guarantee *per se* that new insights can be gained. It is also essential that the standard measures utilized in the analysis of complex networks are appropriately adapted to the specific nature of the network under investigation.

In this thesis, we show how employing all three levels when analyzing ownership networks yields new insights which would otherwise remain unobserved.

Finally, a further regularity can be discovered in real-world networks if they are analyzed at Level 2. This concerns their topological structure.[3] When considering the direction of links, so-called *bow-tie topologies* can be identified. This is a core-periphery structure, with an incoming and outgoing segment. Its core is formed by nodes that are all reachable from each other following chains of directed links. This is called a strongly connected component (SCC).[4] Note that a network can have multiple SCCs. Each of these cores defines a bow-tie structure, with their incoming (IN) and outgoing (OUT) nodes emanate from them. Figure 1.2 illustrates such a topology.

1.1.2 Economic Networks

As mentioned, an extraordinary wide range of natural phenomena can be understood as complex networks. From physics, biology, earth and planetary sciences, finance, computer science and demography to the social sciences. However, to this day economic networks are still acutely underrepresented in this field of study. This issue will be discussed further in Sect. 1.2.3.

To quote the summary given in Schweitzer et al. (2009), appropriately called "Economic Networks: The New Challenges":

> *In summary, we anticipate a challenging research agenda in economic networks, built upon a methodology that strives to capture the rich process resulting from the interplay between agents' behavior and the dynamic interactions among them. To be effective, however, empirical studies providing insights into economic networks from massive data analysis, theory encompassing the appropriate description of economic agents and their interactions, and a systemic perspective bestowing a new understanding of global effects as coming from varying network interactions are needed. We predict that such studies will create a more unified field of economic networks that advances our understanding and leads to further insight. We are still far from a satisfactory identification and integration of the many components, but the recent advances outlined suggest a promising start.*

This thesis responds to these challenges by providing an analysis of economic control in various national networks, next to the global network. Chapter 2 develops a new theoretical framework to measure the flow of control in ownership networks. The 3-level empirical analysis based on this methodology are described in Chaps. 3 and 4. The scope of the datasets covers millions of economic entities in over hundred countries. Finally, Chap. 5 describes a network-formation model giving rise to the

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[3] See Appendix B.3 for an introduction of the notion.

[4] A list of acronyms can be found in front matter of this book.

observed empirical patterns. This offers new insights into possible micro-foundations for the interactions of economic agents.

Our analysis sheds new light on competition in global markets and systemic financial risk. The results are likely to be of interest to a broad audience and have attracted the attention of both the media and economic advisors. In fact, the publications related to Chaps. 3 and 4 were widely covered in the news (see Appendix F) and we have also been contacted by a governmental agency.

1.1.3 Ownership Networks

The specific economic networks studied in this thesis are ownership networks. A detailed introduction to the related economic topics and definitions is given in Sect. 1.2. For the moment it suffices to understand that a percentage of ownership expresses the fraction that a shareholder owns in the firm it has shares in. Shareholders can either be entities who cannot be owned themselves (i.e., natural persons, families, cooperative societies, registered associations, foundations, public authorities or other legal entities) or national or transnational corporations (see Sect. 1.2.1).

Ownership networks are very interesting objects to study, for various reasons. Next to representing an interface between the fields of economics and complex networks, the structure of (international) economic power, or corporate control,[5] is reflected in the network of ownership ties of companies. Ownership networks have been used to measure the impact of globalization or institutional interventions,[6] and they are related to issues of corporate social responsibility and sustainability (Wheeler et al. 2003). They can be understood to exhibit:

> *[…] the historical bargains struck by labor, the state and holders of capital regarding who gets to own and control the economic assets.*
>
> (Kogut and Walker 2001, p. 317)

The study of ownership networks has implications for individual firms:

> *A network of ownership ties represents a unique opportunity to examine how an economy-wide structure of relations affects individual firm diversification events.*
>
> (Kogut and Walker 1999, p. 6)

> *The relationship of capital to the firm is also shaped by the structure of interfirm networks, which influences firm behavior through access to critical resources and information.*
>
> (Aguilera and Jackson 2003, p. 454)

Finally, they are relevant for policymakers:

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[5] This notion will be introduced in Sect. 1.2.1.

[6] This is discussed in Sect. 1.2.3.

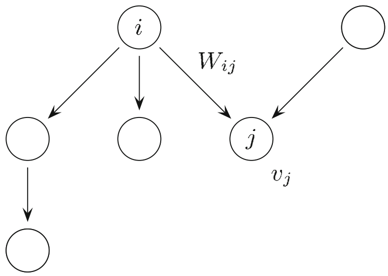

Fig. 1.3 Schematic illustration of a stylized ownership network: nodes represent shareholders and firms, the directed weighted links W_{ij} denote the percentage of ownership; the nodes representing companies carry a non-topological state variable v_j, acting as a proxy for their value or size

> *The analysis of networks of business enterprises has grown to be one of the leading perspectives in the study of business policy, organizational behavior, and public economic policy.*
> (Corrado and Zollo 2006, p. 319)

To obtain a network from ownership data, the percentage of ownership shareholder i has in company j is encoded in the adjacency matrix W by the entry W_{ij}. Figure 1.3 shows a simple illustration of an ownership relation. Note that because the firms can also appear as shareholders, the network does not display a bipartite structure.

Furthermore, the quantity v_j acts as a proxy for the intrinsic or underlying value of the firm j. Common choices are market capitalization, total assets or the operating revenue. While the market capitalization, being defined as the number of outstanding shares[7] times the firm's market price, is a good proxy for the generic value or size of a firm, market prices are only available for listed companies, i.e., firms with shares traded on a stock exchange. Taking total assets as a proxy for the size of firms results in a heavy bias in favor of banks. Operating revenue, defined as the net sales revenue accruing from the primary business operations of a firm, is a measure which is widely available. In Chap. 3, v_j is taken to be the market capitalization of listed companies. In Chap. 4 we employ the operating revenue.

It holds by definition that the sum of shares in a company must add up to 100 %

$$\sum_{i=1}^{n} W_{ij} = 1; \quad j = 1, \dots, n. \tag{1.1}$$

In graph-theoretic terms, the adjacency matrix W is column stochastic. Note however, that sometimes the equality in Eq. (1.1) is not found for the empirical data. The sum can be smaller than 100 % due to unreported shareholdings. Such missing ownership data is nearly always due to their percentage values being very small and therefore negligible. Hence a straight-forward procedure is to normalize the ownership percentages.

An example of a natural measure to derive from these quantities is shareholder i's *portfolio value*:

---

[7] See Sect. 1.2.1.

$$p_i := \sum_{j \in \Gamma(i)} W_{ij} v_j, \tag{1.2}$$

where $\Gamma(i)$ is the set of indices of the neighbors of i. Or in matrix notation $p = Wv$.

The question of what control means in this context and how it can be measured in ownership networks is answered in Chap. 2.

1.2 Elements from Economics

As discussed in the previous sections, it is essential to embed the complex network under study in the context given by its real-world domain. This not only enhances the understanding of the processes forming them but also gives true meaning to the 3-level network analysis.

The issues relating to ownership are discussed in the economics literature from the fields of corporate governance and corporate control. All the concepts revolve around the main entity being analyzed: the corporation. In the following section these themes will be introduced.

Finally, various empirical studies from economics have dealt with the detection and analysis of small ownership patterns, which are discussed in Sect. 1.2.2.

1.2.1 The Corporation: Ownership and Control

A *corporation* is defined as an institution that is a separate legal entity having its own privileges, similar to a natural person. There are many different forms of corporations, most of which are used to conduct business. Corporations have limited liability, can sue, borrow or lend money, buy and sell shares, takeover and merge with other corporations. It must also pay taxes. In a nutshell, *corporate finance* analyzes how the corporations make long-term financial decisions and investigates their financing patterns (Brealey and Myers 1996).

Figure 1.4 shows a simplified illustration of the structure of a corporation. From its business activities the corporation strives to make profits. The money required for new investments can come from different sources. The corporation can finance itself by reinvesting profits. There are also two modes for acquiring external funding. Firstly, debt is sold in the form of bonds to investors or financial institutions. The financial sector also plays an important role in lending money to corporations. Secondly, shares of stock can be issued.

The *stock* represents the original capital paid into or invested in the business by its founders and serves as a security. Hence the stock is also referred to as *equity*