CORE/PERIPHERY SCIENTIFIC COLLABORATION NETWORKS AMONG VERY SIMILAR RESEARCHERS

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Abstract

This paper exploits a network formation game to analyze categorical thinking as a source of segregation. The link between categorical thinking and segregation was recently suggested by Fryer and Jackson (2008). The present model shows how segregation may emerge even when self-interested agents have no a priori motivation to do so; consequently, this paper supports the argument that segregation may not be malevolent in origin.

Keywords: network formation game, scientific collaboration network, inequality, hierarchy.

JEL classification: D85, Z13.

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1 Introduction

Social networks underlie many economic and social activities to the point that certain outcomes cannot be understood without taking into account the specific network structure. Examples and references are numerous[1]. One of the environments in which the key role of a social network is more evident is academics. In scientific production, the association with a group of competent colleagues to exchange information is a strong advantage in order to discover errors, raise research questions, and discern the appropriate ways to solve a problem. This unquestionable significance of networks in understanding scientific activity is one of the reasons that explain the extensive empirical work on this field. Today, in the advent of the information and communication revolution, data on scientific articles and researchers is stored in electronic databases containing thousands of records. With the use of these databases, empirical studies are able to reproduce co-authorship networks (in these networks a link between two researchers exists whenever there exists an article coauthored by them). From there, they are able to represent and analyze the main statistics of the collaboration among researchers.

Empirical research about co-authorship networks is large[2]. Newman (2004), Newman (2001a) and Newman (2001b) analyze the defining statistics of co-authorship networks in Biology, Physics and Mathematics. Laband and Tollison (2000) focus on the importance of informal collaboration relationships in the comparison between networks in Economics and Biology. Hudson (1996) studies the reasons of the increase in the number of coauthors per paper in Economics. But the empirical work that most clearly shows these patterns of collaboration is Goyal, van der Leij and Moraga (2006) (GVM hereafter). This work describes a detailed image of the features of actual co-authorship networks[3].

In spite of the great variety of empirical studies, there is a lack of foundational theoretical models that analyze how individual decisions contribute to the formation of scientific collaboration networks. To the best of my knowledge, Jackson and Wolinsky (1996) and chapter 4 in van der Leij (2006) are the only attempts to compensate this deficiency. This paper proposes an alternative model that aims to contribute to both the literature of social network formation games and to the theoretical literature of the sociology of science.

1.1 Characteristics of co-authorship networks

[1]Calvó-Armengol and Jackson (2004) on learning about job openings through contacts or Kranton and Minehart (2001) on buyer-seller networks are only two examples.

[2]Albert and Barabási (2002) offers a survey of empirical studies about any type of networks.

[3]Although this empirical work refers to the field of Economics, we will argue that the main characteristics of co-authorship networks apply to other fields.

Before introducing the model, let us describe some of the key features of scientific collaboration networks. A surprising characteristic is the small average distance (measured by the shortest path length) between pairs of nodes. This stylized fact of social networks is captured in the famous "six degrees of separation" of John Guare's play[4]. Scientific collaboration networks are not an exception to this phenomenon as GVM shows. The average distance in the Economics co-authorship network they analyzed was 9.47 with a total population of 33,027 nodes (*i.e.* researchers). This regularity extends to other fields. Newman (2004) shows that the average distances are 4.6 in Biology, 5.9 in Physics and 7.6 in Mathematics.

The main features we will focus on refer to the degree-distribution of nodes which tends to show that a small part of the population accumulates a large proportion of links, *i.e.* there is a strong inequality among agents. In particular, GVM found that the 20% of most-linked authors in Economics account for about 60% of all the links. Newman (2004) shows that this phenomenon also extends to co-authorship networks in the fields of Biology, Physics and Mathematics. In each case, the distribution is fat tailed, with a small fraction of scientists having a very large number of collaborators. Moreover, network structures are hierarchical. GVM shows that the best-connected researchers collaborate extensively and most of their coauthors do not collaborate with each other. On the other hand, Newman (2004) found that most of the connections (64%) of an individual's shortest path to other researchers pass through the best-connected of their collaborators, and most of the remainders pass through the next-best connected. GVM illustrates these findings through the local network of J. Stiglitz represented in Figure 1.

[4]Stanley Milgram (1967) pioneered the study of path length through a clever experiment where people had to send a letter to another person who was not directly known to them. In the literature, the diameters of a variety of networks have been measured. These include purely social networks, co-authorship networks, parts of the internet and parts of the world wide web. See Albert and Barabási (2002) for an illuminating account.

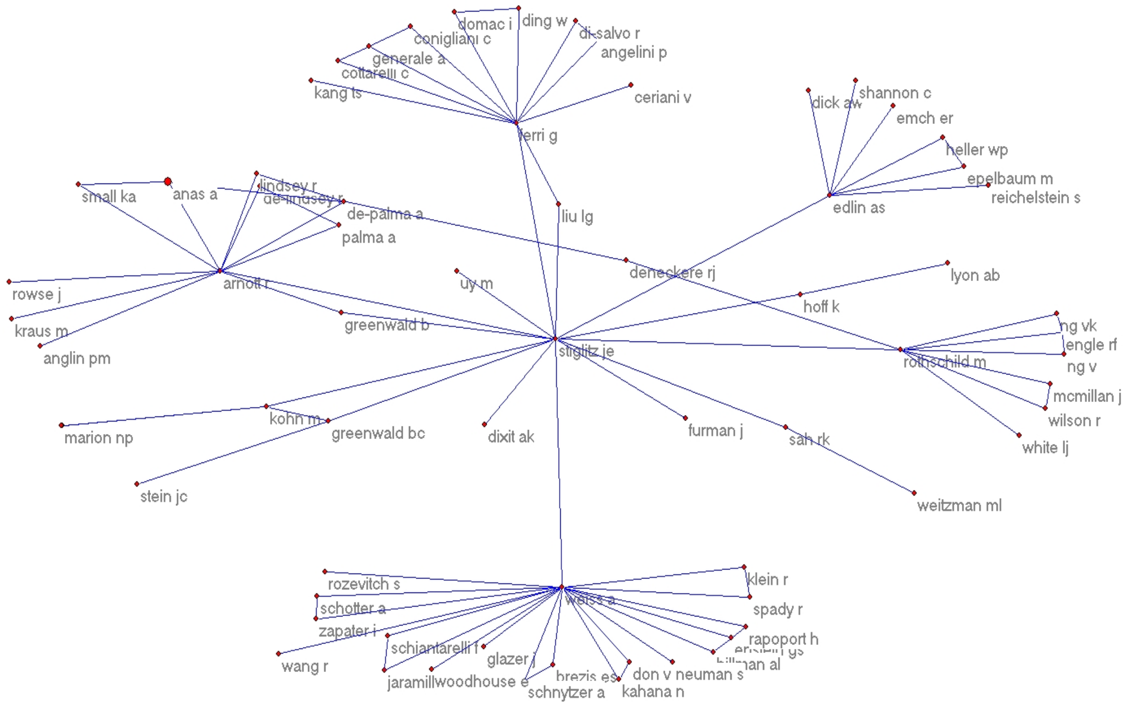

Figure 1: Local network of J. Stiglitz in 1990's

These results lead GVM to conclude that: "the world of Economics is spanned by inter-linked stars". Despite that there is no such conclusion referred to co-authorship networks in other fields, the similarity in the general results showed in Newman (2004) suggests a similar pattern in Biology, Physics and Mathematics. Moreover, GVM analyzes the evolution over the last thirty years and concludes that such a structure is stable over time. A common image in social network analysis and particularly in scientific collaboration networks that illustrates these empirical findings is that of the core/periphery structure[5]. In a core/periphery structure, a group of agents (the core) is densely connected and the complementary set of nodes (peripheral) are simply connected to some member of the core.

Preview of the model and results

This paper proposes a simple static model of network formation in which individuals (interpreted as researchers) make decisions concerning the intensity of their links (interpreted as

[5] Core/periphery networks exhibit (a) very unequal distribution of connections, (b) short distances between nodes, and (c) high clustering. See Cross et al. (2001) for examples of this pattern of social communication structure in small groups and Borgatti and Everett (1999) for a discussion on core/periphery networks.

scientific collaboration relationships) with other researchers through a link formation game. In this model scientific collaboration is stimulated by the scarcity of original ideas and the (arbitrarily small) differences across researchers' levels of talent. The decision of whether to form a collaboration link must consider the trade off between the rewards from collaborating with more talented researchers and the costs derived from using part of their limited processing capacity. In reality, there are many other factors that may affect scientific collaboration decisions. For example, the way the field is organized, researchers' affiliation, and academic or personal complementarities among individuals. It is also obvious that researchers may differ across many additional dimensions other than talent. For example, they can have different levels of productivity or they may specialize on different fields, among others. Nevertheless, this paper aims to show that unequal and hierarchical scientific collaboration networks can arise among (*a priori*) very similar researchers[6]. For this reason, heterogeneity across agents is reduced to one single dimension: agents' talent (which directly affects the value of their scientific contributions). Additional heterogeneities will presumably exacerbate the inequalities this model is already able to reproduce. The results of the model are consistent with the core/periphery structure that is attributed to most of the scientific collaboration and citation networks in the sociological and economic empirical literature (see Mullins et al., 1977).

After introducing the defining elements of the model, the basic assumptions, the payoff function, and the equilibrium concept in section 2, equilibrium networks are characterized in section 3.

1.3 Literature Review

Theoretical models of social network formation can be classified into two groups. On one hand, there is the physics-based modeling of society. This approach treats agents as if they were just matter. That is, agents are non-strategic. This set has its origins in the random graph literature and has examples in sociology and recently in computer science and statistical physics. References of this kind of models are abundant[7] but we will focus on two of them. Jackson and Rogers (2006) proposes a nice, simple and general model of network formation. The authors combine random meeting and network-based meeting in a natural manner and analyze the relevance of these two forces in determining the formation of different kinds of networks (scientific collaboration structures are one of them). On the other hand, Arenas et al (2003) present a stylized model of a problem-solving organization --whose internal communication structure is given by a network-- that can suffer congestion. The authors develop a design problem to determine which kind of network architecture optimizes performance for any given problem arrival rate. Contrarily to the present

[6] Reproducing other stylized facts of empirical coauthorship networks is beyond the scope of the present paper.

[7] See Newman (2003) for a survey. Some examples are Watts (1999), Cooper and Frieze (2003) or Price (1976).

model, the network is fixed and players are non strategic.

The second classification of models involves strategic formation of networks and use game theoretic tools. That is, there is no exogenous prescription of how the network is formed but there is a definition of the rules of the game that agents have to play to form the network (see Jackson (2004) for a survey of this type of models). The model presented here belongs to this group. The paper that more closely relates to this model is chapter 4 in Van der Leij (2006). This author also develops a theoretical model to explain some empirical regularities of research collaboration networks. In that paper the cost of link formation and the specific academic rewards scheme shape the equilibrium network topologies. In the present paper scarcity of original ideas and limited processing capacity drive the incentives of researchers. Unlike Van der Leij (2006), the present model aims to show that equilibrium inequalities can arise even among very similar researchers.

2 General setting

Let N be the set of agents, interpreted as researchers, and let $n = |N|$ be a sufficiently large number. Each researcher is characterized by his level of talent which is exogenous, fixed, and has been randomly generated from a continuous distribution function[8]. In consequence, researchers can be ordered by their level of talent in a well defined ranking. We use natural numbers to label agents according to their position in that ranking. Thus, agent i has $i-1$ researchers with a higher talent. Let h be the commonly known vector of talent endowments and h_i be the i-th element of this vector interpreted as researcher i's amount of talent. Notice that $h_i > h_j$ for any pair of agents such that $j > i$.

The objective of the researchers of this model is to maximize the aggregate value of their scientific contributions. Producing a scientific contribution requires an original idea and some processing work. A researcher is considered to be a coauthor of a scientific contribution either if he creates the original idea or if he contributes some processing effort. Each researcher has both creating and processing capacities.

• Researchers as creators. All agents have a creative capacity that allows them to generate $\rho \in (0,1)$ original ideas.

• Researchers as processors. The processing work can be done either by the creator of the idea or by some collaborator. It is assumed that all researchers have a limited processing capacity so that they can only process I ideas where I is normalized to one.

Notice that it is assumed that agents are able to process more ideas than what they are

[8]The probability of having two agents with the same amount of talent is zero.

able to create by their own means, *i.e.* there is scarcity of original ideas. Consequently, researchers must look for scientific collaborations to obtain original ideas from others and be able to exhaust their processing capacity.

Notice also that all researchers of this model are identical according to their creative and processing capacities. Heterogeneity arises from the differences among agents' level of talent. The value of a scientific contribution depends on the talent of its coauthors[9]. Specifically, $f(h_i, h_j)$ measures the value of a contribution coauthored by i and j ($i = j$ in case of a single-authored contribution). It is assumed that $f(h_i, h_j) > 0$ for any pair $i, j \in N$ and that $\frac{\partial f(h_i, h_j)}{\partial h_k} > 0$ for $k = i, j$, *i.e.* the value of a contribution positively depends on the coauthors' talents. The comparison between the value of a single-authored and a coauthored contribution is parameterized through α as follows. There exists an $\alpha \in \mathbb{R}_+$ such that $f(h_i, h_i) = f(h_i, \alpha h_i)$ for all $i \in N$. Intuitively α marks a threshold level for every researcher; creator i will prefer to process his own ideas rather than collaborating with some researcher whose talent is lower than αh_i. On the contrary, creator i will be willing to collaborate with researchers with a talent higher or equal to αh_i. Thus, when α is high and there is a close-to-homogeneous scientific community, ideas will rarely flow from their creators to others researchers and the number of scientific collaborations will be relatively low. The size of α will depend on various factors. On the one hand, it is true that coauthorships are seriously discounted in the marketplace (a coauthored paper may be worth two thirds of a single-authored paper), but one must also consider that $f(h_i, h_j)$ also captures the beneficial aspects of collaboration, *i.e.* complementarities, advantages from the division of labor or from specialization among others. Parameter α summarizes the aggregate effect of all these different factors and $\frac{1}{\alpha}$ can be interpreted as the incentives of collaboration.

2.1 Description of the game

Agents of this model strategically decide their collaboration intensities with other researchers. Specifically, each agent i will choose the n-dimensional vectors q_i and p_i. The vector $q_i = (q_{i1}, q_{i2}, ..., q_{in})$ represents the distribution of i's original ideas among the rest of researchers. In particular, $q_{ij} \in [0,1]$ denotes the proportion of i's original ideas that researcher i

[9]The number of coauthors of a particular contribution can be either one if the creator decides to work alone or two if he decides to look for some collaborator.

decided to send to j. In consequence, $\sum_{j \in N} q_{ij} = 1$, $\forall i \in N$. Thus, $q_{ij} = 0$ means that i does not consider j as a potential collaborator to process his original ideas whereas $q_{ij} > 0$ involves that j can process some of the i's original ideas. Let $N_i = \{ j \in N : q_{ji} > 0 \}$ be the set of researchers that consider i as a collaborator to process their original ideas and $M_i = \{ j \in N : q_{ij} > 0 \}$ be the set of collaborators to process i's original ideas. The vector $p_i = (p_{1i}, p_{2i}, ..., p_{ni})$ represents the processing efforts of researcher i. In particular, $p_{ji} \in [0,1]$ denotes the processing effort that agent i invests in researcher j's ideas. Thus, $p_{ji} = 0$ means that researcher i invests no time to process ideas coming from j, therefore i does not consider j as a source of original ideas. Whenever $p_{ji} > 0$ agent i will invest some effort to process j's ideas. The processing capacity constraint implies that $\rho \sum_{j \in N} q_{ji} p_{ji} \leq 1$ for all $i \in N$.

Agents i and j are collaborators if either $p_{ij} q_{ij} > 0$ or $p_{ji} q_{ji} > 0$. Thus, mutual consent is required to establish a scientific collaboration relationship. Let Q and P be the $n*n$ matrices agglomerating the vectors q_i and p_i for all $i \in N$. Notice that these scientific collaboration relationships can be represented by weighted and directed links. According to this interpretation, the $n*n$ matrix $G \equiv Q \otimes P$ is a directed graph on N, where entry $g_{ij} \equiv p_{ij} q_{ij} \in [0,1]$ measures the collaboration intensity between i (creator) and j (processor). In general, there exists a link from i to j if and only if $g_{ij} > 0$. In a *core/periphery* network there are two groups of nodes: central nodes constitute the core and they are connected to each other and also to some peripheral node; peripheral nodes are connected to the core but not to each other.

Agents play a game that can be structured in three stages:

• Link formation game: all players strategically and simultaneously announce their q and p vectors. Formally, the strategy space for player i is $S_i = [0,1]^{2n}$. A particular strategy s_i is a pair (q_i, p_i). A strategy profile $s = (s_1, ..., s_n)$ induces a directed-weighted graph $G(s) = Q \otimes P$. We shall use the pair (q_i, p_i) to denote agent i's strategy.

• Creation and distribution of ideas: once the scientific collaboration network is formed, each researcher $i \in N$ creates ρ ideas and distributes them according to q_i.

• Processing of ideas and resolution: Each researcher $i \in N$ processes ideas according to p_i. Then, participants in all scientific contributions receive their payoffs.

Notice that agents only take one decision, in the first stage. As commented above, the objective of the researchers of this model is to maximize the aggregate value of their scientific contributions. Specifically, agent i 's payoffs can be written as:

$$\Pi_i(Q,P) = \rho[\sum_{j\in N} q_{ji}\, p_{ji}\, f(h_j, h_i) + \sum_{l\in N\setminus i} q_{il}\, p_{il}\, f(h_i, h_l)] \tag{*}$$

The first part of this function represents researcher i 's payoff obtained from contributions based on others' original ideas whereas the second part represents the payoff obtained from contributions based on i 's original ideas. These payoffs are the result of multiplying the value of the particular contribution (which depends on the collaborators' talents) by the intensity of their collaboration relationship.

Each researcher $i \in N$ has to choose the optimal pair (q_i, p_i) satisfying the following restrictions:

$$\rho \sum_{j\in N} q_{ji}\, p_{ji} \leq 1 \tag{1}$$

$$0 \leq q_{il} \leq 1 \forall l \in N \text{ and} \sum_{l\in N} q_{il} = 1 \tag{2}$$

$$0 \leq p_{ji} \leq 1 \forall j \in N \tag{3}$$

The first restriction represents the limited processing capacity of agents. Restrictions (2) and (3) derive from the definition of q_i and p_i, respectively. For a given pair (q_{-i}, p_{-i}), the objective function (*) and restrictions (1), (2), and (3) constitute a Linear Programming problem. Given (q^*_{-i}, p^*_{-i}), a pair (Q^*, P^*) is said to be a Nash Equilibrium if (q^*_i, p^*_i) is the solution of this Linear Programming problem for all $i \varepsilon N$. In other words, (Q^*, P^*) is a Nash Equilibrium if $\Pi_i(Q^*, P^*) \geq \Pi_i(q_i, q^*_{-i}, p_i, p^*_{-i})$ for all pairs (q_i, p_i) and for all $i \in N$. Given that the creation of a scientific collaboration link requires mutual consent of the two agents involved and that researchers can announce any p and q vectors they wish satisfying restrictions (1)-(3) (multidimensional strategy space), a huge coordination problem arises. As such, the game displays a multiplicity of Nash Equilibria where mutually beneficial links can be left aside[10]. This is solved if players are allowed to coordinate bilaterally. For this reason, refinements on Nash Equilibrium that allow for coalitional moves are usually applied to this kind of network-formation games[11]. The

[10]For example, a strategy profile in which $p_{ij} = q_{ij} = 0 \;\; \forall \;\; i \neq j$ (resulting in the empty network) is always a Nash Equilibrium.

[11]Contrarily to Bala and Goyal (2000) and others, our model presents directed links but both agents involved in a link benefit from its existence and mutual consent is required to form it; the direction of the link only refers to the flow of ideas. So, in spite of having directed links, we do not formulate the network formation as a non cooperative game.

refinement used here is the Bilateral Equilibrium that is defined as follows:

Definition 1. A pair (Q^*, P^*) is a Bilateral Equilibrium if

- (Q^*, P^*) constitutes a Nash equilibrium and
- for any pair of players $i, j \in N$ and every pair of strategies (q_i, p_i) and (q_j, p_j),

$$\Pi_i(q_i, q_j, q^*_{-i-j}, p_i, p_j, p^*_{-i-j}) > \Pi_i(Q^*, P^*) \Rightarrow \Pi_j(q_i, q_j, q^*_{-i-j}, p_i, p_j, p^*_{-i-j}) < \Pi_j(Q^*, P^*).$$

We shall use the short term BE to refer to this concept. This notion of equilibrium is taken from Goyal and Vega-Redondo (2007); it generalizes the original formulation of pairwise stability due to Jackson and Wolinsky (1996) by allowing pairs of players to modify the intensity of their links simultaneously.

3 Results

Empirical studies such as Goyal, Van der Leij and Moraga (2006) or Newman (2004) show that scientific collaboration networks have a core/periphery structure so that they present a highly unequal and hierarchical distribution of links. This implies that some researchers can be much more active and productive than others and, consequently, they can enjoy a much better scientific reputation. One may think that big intrinsical differences among researchers can constitute the main driving force behind these large inequalities. Nevertheless, this section shows that this is not necessarily the case.

Let $\lfloor a \rfloor$ denote the integer part of $a \in \mathbb{Q}$. For every $i \in N \setminus \{1\}$ let us define player $k_i \in N$ as follows:

$$k_i = \begin{cases} 1 & , if\ i < \frac{1}{\rho} + 2\ and\ g_{12} = 1 \\ \lfloor 1 + \rho(i-1) \rfloor & , otherwise. \end{cases}$$

The main result of the paper can be stated as follows:

Theorem 1. If $h_{k_i} \geq \alpha h_i$ for any $i \in N \setminus \{1\}$, any BE network must hold a core/periphery structure with the following characteristics:

(a) Central nodes are the $\lfloor \rho n \rfloor$ most talented researchers and they are the only ones exhausting their processing capacity,

(b) $g^*_{11} = 1$ when $h_2 < \alpha h_1$; otherwise, $g^*_{12} = 1$. And finally,

(c) for any $i \in N \setminus \{1\}$,

- $g^*_{ik_i} = 1$ if i is neither the most nor the least talented researcher in N_{k_i} and

- $g^*_{ik_i} \in (0,1]$, otherwise. In this case, a unique researcher $l \neq k_i$ holds $g^*_{il} \in (0,1)$ where $l \in \{k_i+1, k_i+2, i\}$.

The proof presented in the appendix proceeds by showing the equilibrium properties of P^* (Lemma 1 and Corollary 1) and Q^* (Lemmas 2-5). This theorem characterizes equilibrium network candidates when the incentives of collaboration are sufficiently high. Notice that conditions (a), (b) and (c) narrow the set of candidates to a great extent. In particular, conditions (b) and (c) specify the intensity of most of the links in equilibrium. Only the intensity of the links of each processor i with the most and the least talented agents in N_i remain unspecified and, consequently, the set of equilibrium candidates is not a singleton.
Next proposition demonstrates existence.

Proposition 1. If $h_{k_i} \geq \alpha h_i \ \ \forall \ \ i \in N \setminus \{1\}$, the network holding the conditions of Theorem 1 and $p^*_{ij} = 1$ for any pair of researchers i, j such that $i \in N_j$ is a BE.

Proof. It is easy to see that when conditions of Theorem 1 hold, all researchers are transmitting all their original ideas to the best possible destination(s), given what all others are doing, and these destinations process the ideas coming from the best possible origins, given what all others are doing. Moreover, since $p^*_{ij} = 1$ for all $i \in N_j$, all ideas are processed with the maximum effort. In consequence, no agent or pair of agents will have incentives to deviate neither unilaterally nor bilaterally.

Since it is always possible to set up such a network, it can be concluded that a BE exists. However, this BE network is not unique. Specifically, one can think on alternative equilibria where $p^*_{ij} < 1$ and $p^*_{ij} q^*_{ij} > 0$ where i is the least talented agent in N_j. Nevertheless, these alternative equilibria will hold the main features described in Theorem 1, so they are core/periphery structures.
The main implications of these results can be outlined as follows:

1. *Scarcity of ideas and equilibrium inequalities*. From part (a) of the Theorem, it can be concluded that in equilibrium the population of researchers can be split into two subgroups: the $\lfloor \rho n \rfloor$ most talented agents are able to exhaust their processing capacity because they are receiving original ideas from others whereas the rest of researchers will not use all their processing capacity. This is consistent with the core/periphery structure that is attributed to most of the

scientific collaboration and citation networks. In these structures, Borgatti (2005) claims that innovations flow from the periphery to the core as this result suggests. Whenever incentives of collaboration are relatively large, *i.e.* whenever α is relatively small, ideas will accumulate on the most talented researchers of the population. The relative size of that privileged subgroup of researchers will be inversely proportional to the scarcity of original ideas. Without scarcity, $\rho \geq 1$, inequality will not exist since all agents will be able to exhaust their processing capacity.

2. *Inequality and hierarchy*. Apart from being unequal, equilibrium network candidates present a strong hierarchy as illustrated by Lemma 4 and point (c) of Theorem 1. That lemma states that whenever there is an active collaboration relationship between two agents l and i in which i processes the original ideas of l, any agent j (different from i) such that $h_j > h_l$ should send all their original ideas to agents with a talent higher or equal than h_i. Otherwise, agents i and j can profitably deviate by increasing the intensity of their collaboration relationship in which i processes the original ideas of j. This result imposes a clear hierarchical structure on equilibrium networks, because it implies that the higher is the talent of a researcher the more talented are his collaborators. This will raise the inequalities among equilibrium payoffs because the highly talented researchers will collaborate with each other and this will increase the differential between the value of their contributions and the contributions of the less talented researchers. Notice that this result holds for any arbitrarily small (non-zero) differences among agents' talents whenever the incentives of collaboration -represented by the inverse of α - are relatively high.

3. *Incentives of collaboration and ex-ante heterogeneity*. The condition $h_{k_i} \geq \alpha h_i$ establishes a relationship between the distribution of talents and the incentives of collaboration. The lower is α (*i.e.* the higher are the incentives of collaboration) the lower can be the difference between h_{k_i} and h_i for this condition to hold. Notice that even for arbitrarily small (non-zero) differences among agents' talents, there will always exist a sufficiently small α under which the above results will still hold and equilibrium inequalities will arise. Thus, *very similar researchers will self-organize forming hierarchical and highly unequal equilibrium networks when the incentives of collaboration are sufficiently high. There is no need to impose huge a priori differences among researchers to reproduce those collaboration structures*[12].

On the other hand, if the incentives of collaboration were low creators would demand high levels of talent to the processor(s) of their ideas. Thus, if the talent differentials are not sufficiently

[12] This contrasts with the results of Van der Leij (2006) in which a minimum degree of heterogeneity among agents is required in order to reproduce the empirical results about in-degree inequality.

big the amount of scientific collaborations will decrease because some researchers will prefer to process their own ideas. The implications of having relatively low incentives of collaboration are summarized below.

Proposition 2. Given h, top ranked researchers accumulate the scientific collaborations (if any) whose aggregate number is inversely related to α. Thus, BE networks range from the core/periphery structure described above (when $h_{k_i} \geq \alpha h_i$ for any $i \in N \setminus \{1\}$) to the empty network (when $h_j < \alpha h_i$ for any pair $i, j \in N$).

Proof. By Lemmas (1) and (3) links (if any) will accumulate on the most talented researchers. Lemma (4) still applies, so that links should maintain a strict order in equilibrium. When $h_{k_i} < \alpha h_i$ for some i, Lemmas 1 and 2 imply that $g_{ii}^* = 1$, *i.e.* agent i will retain his own ideas, when (i) $\rho \sum_{l \varepsilon N} q_{lj}^* \geq 1$ for any $j < k_i$ and (ii) $h_i < h_l$ for any $l \in N_j$. For a given h, the number of those researchers will increase with α. Equilibrium networks behave accordingly.

Having more agents who do not share their own ideas has some immediate implications. Since the number of ideas that flow through the network will be lower, the number of top ranked researchers who exhaust their processing capacity can be lower than $\lfloor \rho n \rfloor$. That means that some processing capacity of high talented researchers will be wasted involving efficiency losses. Furthermore, the lower density of connections can involve the emergence of isolated agents until reaching the extreme case of having an empty network of collaborations (*i.e.* when no one shares their own ideas).

The next example illustrates a BE network structure for the case of sufficiently big incentives of collaboration.

Example 1. Let us assume that $n = 70$, $\rho = 0.1$, $h_{k_i} \geq \alpha h_i$ for any $i \in N \setminus \{1\}$ and $h_2 \geq \alpha h_1$. Since agents' processing capacity is normalized to one, in this example agents must receive ideas from, at least, ten different origins in order to exhaust their processing capacity. By Proposition 1, the matrix Q^* can be described as follows:

$q_i^* = (1,0,0,...,0)$ $\forall$ $i \in [2,11]$,

$q_i^* = (0,1,0,0,...,0)$ for $i = 1$ and $i \in [12,20]$,

$q_i^* = (0,0,1,0,...,0)$ $\forall$ $i \in [21,30]$,

$q_i^* = (0,0,0,1,0,...,0) \;\; \forall \;\; i \in [31,40]$,

and so on.

Whereas the matrix P^* will be:

$$p_{i1}^* = \begin{cases} 1 & , if \;\; i \in [2,11]; \\ 0 & , otherwise. \end{cases}$$

$$p_{i2}^* = \begin{cases} 1 & , if \;\; i = 1 \; or \; i \in [12,20]; \\ 0 & , otherwise. \end{cases}$$

$$p_{i3}^* = \begin{cases} 1 & , if \;\; i \in [21,30]; \\ 0 & , otherwise. \end{cases}$$

$$p_{i4}^* = \begin{cases} 1 & , if \;\; i \in [31,40]; \\ 0 & , otherwise. \end{cases}$$

and so on.

The BE network is illustrated in Figure 2[13].

Researchers 1-7 constitute the core. They receive original ideas from others until exhausting their processing capacity. Agents 8-70 do not receive any idea from others and they only send their ideas to a member of the core. Moreover, there is a strict order in the collaboration pattern; agents with a higher talent can collaborate with higher talented researchers. As a consequence, members of the core will enjoy a payoff differential with respect to peripherals because (i) they will produce a higher number of contributions and (ii) they will collaborate with the most talented researchers.

[13]In our scientific collaboration network links are directed in the sense that ideas flow from one collaborator to the other. This direction is not represented in Figure 2 but is captured by the matrices P^* and Q^* described above.

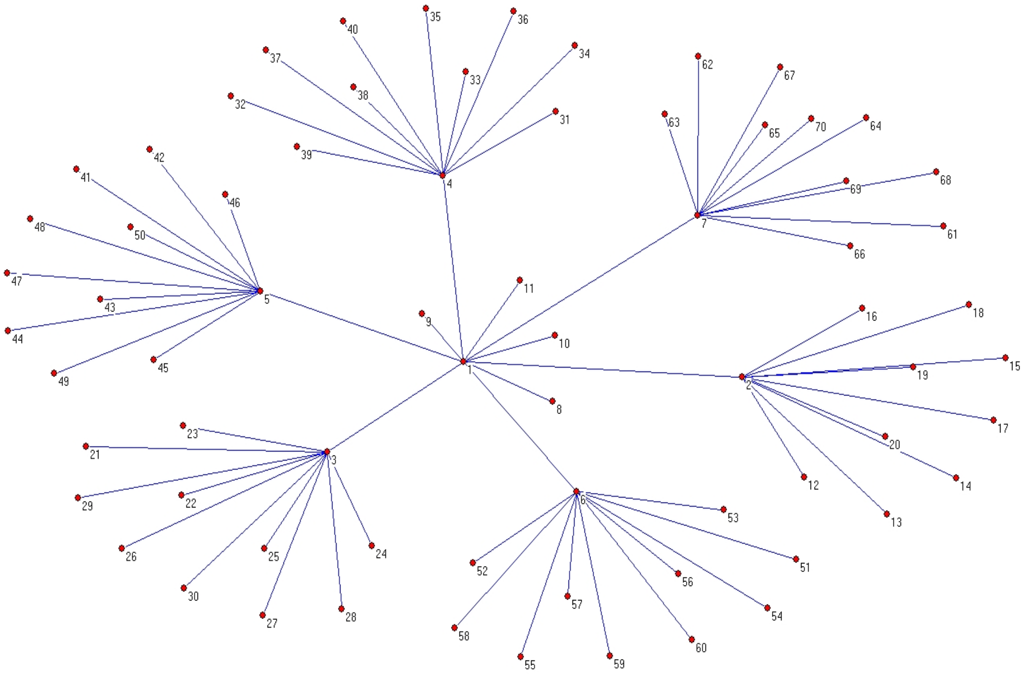

Figure 2: Example with n=70 and $\rho = 0.1$

4 Conclusion

In spite of the large body of empirical research about scientific collaboration networks, there is a lack of foundational theoretical models that analyze how individual decisions contribute to scientific collaboration network formation. This paper proposes a natural network formation game in which heterogeneity among researchers and limited processing and creative capacities drive agents incentives regarding scientific collaboration. The model allows us to figure out the conditions under which very similar researchers will organize themselves forming unequal and hierarchical scientific collaboration networks as is observed in the real-world. The results of the model are consistent with the core/periphery structure that is attributed to most of the scientific collaboration and citation networks in the sociological and economic empirical literature.

A sensitive researcher might read this paper as expressing an impression on the part of the author that top people are top, to some extent, because of their ability to develop the ideas of others, not because of their ability to develop better and/or more ideas than others. This view of the world is, of course, difficult to sustain. By imposing only one source of heterogeneity, the present paper intends to highlight that the big inequalities observed in reality may have other causes apart from high ex-ante inequalities. It is very reasonable to believe that more talented people will also get more and better ideas than others but presumably this will amplify the ex-post inequalities that this model is already able to reproduce even among very similar individuals.

Appendix

Proofs

Proof of Theorem 1. The proof can be decomposed into 5 steps. In what follows, each of these steps is formally embodied by a corresponding lemma.

Lemma 1. For any given Q and for any $i \in N$, p_i^* should satisfy:

(i) $\rho \sum_{l \in N} q_{li} p_{li}^* = \min\{\rho \sum_{l \in N} q_{li}, 1\}$,

(ii) for any two agents $j, l \in N_i$ such that $h_j > h_l$, it must be satisfied that $p_{ji}^* \geq p_{li}^*$, and

(iii) $p_{li}^* \in (0,1)$ for at most one agent $l \in N_i$.

Proof of Lemma 1. For a given Q, agent i's best response p_i^* should maximize his payoff (*) and hold restrictions (1) and (3), *i.e.* p_i^* must be the solution of a Linear Programming problem[14]. As such, p_i^* must be one of the vertices of the polytope defined by restrictions (1) and (3). Conditions (i)-(iii) specify the characteristics of this vertex and are proved in turn: (i) Notice that restrictions (1) and (3) already imply that

$$\rho \sum_{l \in N} q_{li} p_{li}^* \leq \min\{\rho \sum_{l \in N} q_{li}, 1\} \; \forall \, \mathrm{p_i}.$$

By contradiction with the statement of the Lemma, let us assume that $\rho \sum_{l \in N} q_{li} p_{li}^* < \min\{\rho \sum_{l \in N} q_{li}, 1\}$. This implies that for some $j \in N_i$, there exists a $p_{ji}' > p_{ji}^*$ holding restrictions (1) and (3). Since agent i's payoff depends positively on p_{ji}, this agent can profitably deviate by choosing p_{ji}' instead of p_{ji}^*. Thus, the above inequality cannot hold in equilibrium. (ii) By contradiction let us assume that the equilibrium vector p_i^* holding restrictions (1) and (3) holds $p_{li}^* > p_{ji}^*$ for some pair of players $j, l \in N_i$, such that $h_j > h_l$. It is claimed that agent i can profitably deviate by choosing

[14] It is easy to see that this solution is unique because $h_i \neq h_j$ for any pair $i, j \in N$.

$p_{ji}' \in (p_{ji}^*, 1]$ and $p_{li}' \in [0, p_{li}^*)$. To assure that restriction (1) still holds after the deviation the following must be satisfied:

$$(p_{ji}' - p_{ji}^*)q_{ji} = (p_{li}^* - p_{li}')q_{li}$$

It is easy to check that the pair

$$p_{ji}' = min\{1, p_{ji}^* + p_{li}^* \frac{q_{li}}{q_{ji}}\}$$

$$p_{li}' = p_{li}^* - (p_{ji}' - p_{ji}^*)\frac{q_{ji}}{q_{li}}$$

satisfies the above conditions, and so restrictions (1)-(3). The marginal payoff for the deviator i is:

$$\Delta\Pi_i = \rho[(p_{ji}' - p_{ji}^*)q_{ji} f(h_j, h_i) + (p_{li}' - p_{li}^*)q_{li} f(h_l, h_i)]$$

Using the definition of p_{li}' it can be written that:

$$\Delta\Pi_i = \rho(p_{ji}' - p_{ji}^*)q_{ji}[f(h_j, h_i) - f(h_l, h_i)] > 0$$

Therefore $p_{li}^* > p_{ji}^*$ cannot hold in equilibrium.

(iii) Assume by contradiction that $p_{ji}^*, p_{li}^* \in (0,1)$ for some pair of agents $j, l \in N_i$ such that $h_j > h_l$. The deviation considered in case (ii) is also possible and generates a positive marginal payoff to the deviator. In consequence, p_{ji}^* and p_{li}^* cannot be between 0 and 1 in equilibrium.

The implications of Lemma 1 can be summarized as follows. Let t_i be the least talented agent in N_i holding $\rho\sum_{j\in N: h_j > h_{t_i}} q_{ji} < 1$.

Corollary 1. For any given Q and for any $i \in N$ and $l \in N_i$, p_i^* is such that:

$$p_{li}^* = \begin{cases} 1 & , if\ h_l > h_{t_i} \\ \min\{(1 - \rho \sum_{j\in N: h_j > h_l} q_{ji})\frac{1}{q_{li}}, 1\} & , if\ h_l = h_{t_i} \\ 0 & , otherwise \end{cases}$$

Notice that, given ρ and Q, there is a unique P satisfying the above conditions, *i.e.* there is unique equilibrium candidate for P. Next Lemmas characterize Q^*.

Lemma 2. For any pair of players $i, j \in N$, $q_{ij}^* > 0$ only if (i) $p_{ij}^* > 0$ and (ii) $h_j \geq \alpha h_i$.

Proof of Lemma 2. Assume by contradiction with (i) that $q_{ij}^* > 0$ and $p_{ij}^* = 0$. Since $\rho < 1$, there exists some agent $r \in N$ such that $\rho \sum_{l \in N} q_{lr}^* < 1$. By Lemma 1, $p_{lr}^* = 1 \;\; \forall l \in N_r$. Agents i and r can jointly deviate by choosing $p_{ir}' = 1$, $q_{ir}' \in (q_{ir}^*, 1]$, and $q_{ij}' \in [0, q_{ij}^*)$. To satisfy restrictions (1)-(3) after the deviation, the following must hold:

$$q_{ir}' - q_{ir}^* = q_{ij}^* - q_{ij}'$$

$$1 - \rho \sum_{l \in N} q_{lr}^* \geq \rho (q_{ir}' - q_{ir}^*)$$

By setting:

$$q_{ir}' = min\{1, q_{ir}^* + q_{ij}^*, q_{ir}^* + (\frac{1}{\rho} - \sum_{l \in N} q_{lr}^*)\}$$

$$q_{ij}' = q_{ij}^* + (q_{ir}' - q_{ir}^*)$$

the above conditions are satisfied. The deviators' marginal payoffs are:

$$\Delta \Pi_r = \Delta \Pi_i = \rho (q_{ir}' - q_{ir}^*) f(h_i, h_r)$$

Since $q_{ir}' > q_{ir}^*$ and $f(h_i, h_r) > 0$, it can be concluded that i and r will jointly deviate and q_{ij}^* cannot be positive when $p_{ij}^* = 0$.

Assume by contradiction with (ii) that $q_{ij}^* > 0$ and $h_j < \alpha h_i$. Since $\rho < 1$, either i has some free processing capacity or $q_{li}^* > 0$ for some $l \in N$ such that $h_l < h_i$. In such a case, it is easy to see that agent i can profitably deviate by retaining (part of) the original ideas that she was sending to j.

Lemma 3. Consider three different players $i, j, r \in N$ such that $h_i > h_r$. Whenever $q_{jr}^* > 0$, player i must hold that $\rho \sum_{l \varepsilon N} q_{li}^* \geq 1$.

Proof of Lemma 3. Consider by contradiction an equilibrium in which $q_{jr}^* > 0$ and

$\rho\sum_{l\in N}q_{li}^{*}<1$ for some agent $i\neq j$ such that $h_i > h_r$. Notice that, by restriction (2), $q_{jr}^{*}>0$ implies that $q_{ji}^{*}<1$. Notice also that, by Lemma 1, $p_{li}^{*}=1$ for all $l\in N_i$. Let us consider that i and j jointly deviate by choosing $p_{ji}'=1$, $q_{ji}'\in(q_{ji}^{*},1]$, and $q_{jr}'\in[0,q_{jr}^{*})$. In order to assure that restrictions (1)-(3) still hold after the deviation the following conditions must be satisfied:

$$q_{ji}'-q_{ji}^{*}=q_{jr}^{*}-q_{jr}'$$

$$1-\rho\sum_{l\in N}q_{li}^{*}\geq\rho(q_{ji}'-q_{ji}^{*})$$

It is easy to check that the pair

$$q_{ji}'=min\{1,q_{ji}^{*}+q_{jr}^{*},q_{ji}^{*}+(\frac{1}{\rho}-\sum_{l\in N}q_{li}^{*})\}$$

$$q_{jr}'=q_{jr}^{*}-(q_{ji}'-q_{ji}^{*})$$

satisfies the above conditions, and so restrictions (1)-(3). The marginal payoff for the deviators i and j can be written as follows:

$$\Delta\Pi_i=\rho(q_{ji}'-p_{ji}^{*}q_{ji}^{*})f(h_j,h_i)$$

$$\Delta\Pi_j=\rho[(q_{ji}'-p_{ji}^{*}q_{ji}^{*})f(h_j,h_i)-(q_{jr}^{*}-q_{jr}')p_{jr}^{*}f(h_j,h_r)]$$

Since $q_{ji}'>q_{ji}^{*}$ and $p_{ji}^{*}\leq1$, we can conclude that $\Delta\Pi_i>0$. With respect to $\Delta\Pi_j$, we can use the definition of q_{jr}' and some simple algebra to write:

$$\Delta\Pi_j\geq\rho(q_{ji}'-q_{ji}^{*})(f(h_j,h_i)-f(h_j,h_r))$$

Since $q_{ji}'>q_{ji}^{*}$, $h_i>h_r$, and $i\neq j$ we can conclude that $\Delta\Pi_j>0$. In consequence, both agents will agree on that deviation and the situation introduced in the beginning of the proof cannot hold in equilibrium.

Using Lemmas (1)-(3) it can be concluded that in equilibrium original ideas will accumulate on the most talented researchers whenever α is sufficiently low. In particular, if $h_{k_i}\geq\alpha h_i$ for any $i\in N\setminus\{1\}$ point (a) of Theorem 1 immediately follows since ρn is the total number of ideas and each agent can process exactly one idea. Point (b) is trivial. To prove point (c) two extra lemmas are needed.

Lemma 4. If $q^*_{li} p^*_{li} > 0$ for some pair of agents $l, i \in N$, then q^*_{jr} cannot be positive for any pair of agents $j, r \in N$ such that (i) $j \neq i$, (ii) $h_j > h_l$, and (iii) $h_r < h_i$.

Proof of Lemma 4. Let us assume by contradiction that $q^*_{jr} > 0$ under conditions (i)-(iii) stated in the Lemma. Notice that $q^*_{jr} > 0$ implies that $q^*_{ji} < 1$. Notice also that $p^*_{li} > 0$. Let us consider that i and j jointly deviate by choosing $p_{ji}' = 1$, $q_{ji}' \in (q^*_{ji}, 1]$, $q_{jr}' \in [0, q^*_{jr})$, and $p_{li}' \in [0, p^*_{li})$. In order to assure that restrictions (1)-(3) still hold after the deviation the following conditions must hold:

$$q_{ji}' - q^*_{ji} = q^*_{jr} - q_{jr}'$$

$$q_{ji}' - p^*_{ji} q^*_{ji} = q^*_{li}(p^*_{li} - p_{li}')$$

By Lemma 1, $q^*_{li} p^*_{li} > 0$ and $h_j > h_l$ imply that $p^*_{ji} = 1$ whenever $q^*_{ji} > 0$. Therefore, the second condition can be written as follows:

$$q_{ji}' - q^*_{ji} = q^*_{li}(p^*_{li} - p_{li}')$$

It is easy to check that $p_{ji}' = 1$ and

$$q_{ji}' = min\{1, q^*_{ji} + q^*_{jr}, q^*_{ji} + q^*_{li} p^*_{li})\}$$

$$q^*_{jr} + q_{jr}' = q^*_{ji} + q_{ji}'$$

$$p_{li}' = p^*_{li} - \frac{q_{ji}' - q^*_{ji}}{q^*_{li}}$$

satisfy the above conditions. The marginal payoff for the deviators can be written as follows.

$$\Delta\Pi_i = \rho[(q_{ji}' - p^*_{ji} q^*_{ji}) f(h_j, h_i) + q^*_{li}(p_{li}' - p^*_{li}) f(h_l, h_i)]$$

Substituting the last condition stated above we obtain:

$$\Delta\Pi_i = \rho q^*_{li}(p_{li}' - p^*_{li})(f(h_l, h_i) - f(h_j, h_i))$$

Since $p^*_{li} > p_{li}'$, $h_i \neq h_j$, and $h_j > h_l$ then $\Delta\Pi_i > 0$. On the other hand,

$$\Delta\Pi_j = \rho[(q_{ji}' - p^*_{ji} q^*_{ji}) f(h_j, h_i) + p^*_{jr}(q_{jr}' - q^*_{jr}) f(h_j, h_r)]$$

Using the previous conditions we obtain:

$$\Delta\Pi_j = \rho(q^*_{jr} - q_{jr}')(f(h_j, h_i) - p^*_{jr} f(h_j, h_r))$$

Since $q^*_{jr} > q_{jr}'$, $h_i \neq h_j$, $h_i > h_r$ and $p^*_{jr} \leq 1$, then $\Delta\Pi_j > 0$. In consequence, both agents will deviate and the original situation cannot hold in equilibrium.

Lemma 4 establishes a strict order in the collaboration relationships. In particular, it implies that the best destination of player i's ideas in equilibrium will be the most talented agent with some available capacity after processing the ideas of the players with a talent higher than h_i. Thus, when $g^*_{11} = 1$, the best destination for i's original ideas is agent $j \in N$ such that $j \in (\rho(i-1), \rho(i-1)+1]$. On the other hand, when $g^*_{12} = 1$, j is the best possible destination for i's ideas except when the ideas of those agents with a higher talent, excluding 1, do not exhaust agent's 1 processing capacity. In such a case, agent 1 is the best possible processor of player i's ideas. In general agent k_i, defined in the main text, summarizes all these conditions and describes the best destination of player i's original ideas in equilibrium.

Lemma 5. For any $i \in N \setminus \{1\}$, $q^*_{ik_i} = 1$ if $h_i > h_{t_{k_i}}$. Otherwise, $q^*_{ik_i} \in (0,1]$ and $q^*_{il} = 1 - q^*_{ik_i}$ where $l = \{k_i + 1, k_i + 2, i\}$.

Proof of Lemma 5. Since $\rho < 1$, notice that $h_{k_i} > h_i$; thus, $k_i \neq i$. By contradiction, assume that there exists an agent $l \in N_{k_i}$ such that $h_l \in [h_{t_{k_i}}, h_i)$ and $q^*_{ik_i} < 1$. By Lemma 2, $p^*_{lk_i} > 0$. This contradicts Lemma 4. On the other hand, if $i = t_{k_i}$ and $\rho \sum_{l \in N_{k_i} : h_l \geq h_i} q_{lk_i} > 1$ then agent i will have to send part of his original ideas to an additional destination. By Lemma 4, agent i will be the most talented agent sending his ideas to player j for any $j \in N$ such that $h_j < h_{k_i}$. Thus, by Lemma 1, $p^*_{ij} = 1$ for any j such that $h_j < h_{k_i}$ and $q^*_{ij} > 0$. Lemmas 2 and 4 imply that the additional destination of i's original ideas may be one of the following:

- $k_i + 1$ if $h_{k_i+1} > \alpha h_i$,
- i if $h_{k_i+1} \leq \alpha h_i$ or
- $k_i + 2$ if $h_{k_i+2} > \alpha h_i$ and $k_i + 1 = i$

Combining Lemmas 1-5, point (c) directly follows.

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