A game-theory modeling approach to utility and strength of interactions dynamics in biomedical research social networks

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November 9, 2016

Abstract

What would happen if researchers in a community were given the same amount of resources and then set free to interact among each other? How would these resources be distributed in the population after many interactions? The final result may be determined by the researchers' social and political power, an by their prestige. Nevertheless, all these attributes depend, to a certain degree, on the research collaboration social network in which scientists are embedded. Here we develop a model based on the Prisoner's Dilemma implemented on a collaboration network. With this model we explore the distribution of resources and the dynamics of the strengthening or weakening of collaboration connections among partners, as scientists cooperate or defect in order to gain access to others' resources. The network is based on data about projects that were awarded with a grant. In this sense, we assume that resources are funds, equipment and time. We define Fitness as how much access a researcher has to the resources of his collegues. We tested our simulation on the real biomedical research network and compared the results with an Erdös-Renyí, a Watts-Strogatz small-world and Barabási-Albert topologies. Different topologies display different fitness and connections strength distributions. Moreover, the distribution of fitness and connections strength in the researchers network is similar to that of Barabási-Albert and Watts-Strogatz topologies, respectively. We believe that fitness distribution in the researchers network suggests that there are socio-cultural mechanisms governing the network that produce an asymmetric distribution of resources. The high distribution of strong connections might reflect some sort of subordination among researchers by which they are morally obliged to cooperate by the same socio-cultural mechanisms.

The range around the threshold that regulates the decision to cooperate or defect according to the agent's historical balance between utility and strength of collaborative relationships and carrying capacity of the system is small, suggesting that there is a region in which a phase transition takes place from a population of cooperators to a population of defectors. Simulations like this may help to develop science policies to promote fair distribution of resources.

1 Introduction

Notes:

- We change utility for fitness. Utility seems a better concept in order to reflect players' preferences.

- Choosing a strategy depends on the balance η' equation –look at page 9. This equation states that the probability of an agent to cooperate increases as: a) its utility increases –as it moves away from 0, or; b) The strength of the connection with its peers increases –as it moves away from 0, or; c) both increases.

  $\eta_i = \frac{\langle f_i \rangle + \langle w_{ij} \rangle_j}{2}$

- En la pagina 9 decimos que "In order for the agent to choose to cooperate or defect, a degree of willingness to cooperate is assigned to each agent." No estoy seguro que "degree of willingness to cooperate" sea la mejor manera de decirlo, mi duda est en la palabra "degree", por lo que cambié la oración a: The probability for an agent to cooperate or defect depends on a number that referes to a historical balance between average utility and the average strength of the connections with its neigbors.

Collaboration has become a cornerstone in biomedical research today. In contrast to physics which has a long history and experience in collaborative projects, biology is only recently becoming an evermore collaborative discipline[1]. Biology has an interesting record in such matters because scientific collaboration means something different to different branches of biology: molecular biology has traditionally been a research activity of small laboratories[2, 3], whereas in natural history there has been data and samples exchange since the $XVII^{th}$ century[4, 5]. Despite the differences in culture and practices, the Human Genome Project made collaboration a central feature of biology.

Nowadays it is widely acknowledged that collaboration takes many forms, from sharing of biological samples and biobanking to international groups in charge of helping research communities to harmonize and share their data. Sharing resources such as equipment, funds, and time is critical; building trust among scientists is fundamental. Also, resources are mobilized in order to create strategic alliances.

The analysis of cooperation in scientific research has been the subject of a number of studies [1, 7, 8, 9, 10, 3, 5]. This is not surprising since cooperation and competition are quite important in today's academic success. How does collaboration happen within a competitive academic environment and what kind of payoff is present in these settings were questions considered recently by Wardil and Hauert [20] in the context of cooperation in multi-authored publications. Also, the role of game theory over complex scientific information and collaboration networks has attracted attention, mainly focusing on how long-term strategies may shape different scenarios for Nash equilibria [21]. Prisoner's Dilemma has been used in the study of impact factor and collaboration [13, 14].

Even with all these research efforts, cooperation in the context of scientific collaboration is still loosely defined and the long term dynamics of academic cooperation (and its consequences) are yet to be fully elucidated. Furthermore, to our current knowledge, there has been no use of game theory and complex network analysis for understanding how the topology of scientific collaboration networks affects access to resources among individuals present in the network [1]. Our work aims to contribute to our current understanding on the matter, specially when agents have to maximize their access to resources while taking care of their collaboration links.

In this article we explore the network effect on the distribution of players having access to certain amount of resources from other players in the network and the distribution of the strength of connections among them. Particularly, we implemented two games played simultaneously: one for maximazing individual utility based on the iterated Prisoner's Dilemma; the other, a coordination game for maximazing the connection strength between players. We are interested in how they affect each other in the context

[1] For an account of scientific collaboration and definitions, please refer to [6].

of a network of scientific collaboration under the idea that while researchers are interested in maximazing their utilities, they also know that it is important to invest in building collaborative relationships. These two behaviors are explored in a biomedical research community of México.

In the context of our paper, utility represents the preference for having access to the resources of others. Maximazing utility means that the player is increasing its access to the resources of other players. The value of the Utility function for a player is the sum of the payoffs of playing with his neighbors. The opossing force comes from the other concurrent game: players trying to maximize the strength of their connections to other players. In the coordinating game the best strategy is to adopt the same strategy as the other player, as it pays the most regardless of cooperation or defection in the utility game. When both cooperate the interaction gets a positive payoff, when both defect, the interaction doesn't get affected; but if they anti-coordinate, then the interaction looses. Finally, cooperation is a central feature of scientific work. For our biomedical network, cooperation can be thought of as sharing resources such as time, students, equipment, even money. Examples of defection to a cooperator are ghost authorship or prestige authorship.

The manuscript is structured in five sections. First we describe *FOSISS*, the main program for grants destined to biomedical applied research in México. This is the source of the database from which we created the researchers collaboration network. Next we describe our model and the different network topologies on which we explored it. We then present our results and discuss them briefly. In the last section we draw some final remarks and conclusions.

2 Biomedical research: CONACyT and FOSISS

CONACyT (National Council of Science and Technology) is the Mexican government entity in charge of promoting the development of science and technology. Among CONACyT's functions are to develop science and technology policies according to national needs and demands, to advise the different instances of government on scientific and technological topics, to promote the creation of research networks among the scientific community, to grant scholarships for masters and doctoral studies, and to manage different trusts intended to fund individuals and groups for scientific and technological research.

In the year 2002 CONACyT, along with other government agencies and entities, created sectoral funds to cover and equally promote research capacities of different areas such as energy, agriculture and health. Technological innovation is fostered by the generation of human resources and by helping research groups to consolidate. It is expected that the knowledge generated under the sponsorship of these funds will be the product of applied research that attends national public needs, and promotes economic growth.

FOSISS or Sectoral Fund for Health and Social Security Research (*Fondo Sectorial en Investigación en Salud y Seguridad Social*) is one of such funds. FOSISS is constituted by CONACyT, SSA, IMSS and ISSSTE,[2] being all of them the major public health providers and research institutions in the country. Every year CONACyT opens a call for funds limited to a set of health research areas previously defined by a group of experts. Such areas range from public health issues to chronic and degenerative diseases.

Eligibility is open to public and private health research sectors, however most applicants are public universities and research institutions. From 2002 through 2013, there were 91 institutions funded that comprised 4988 researchers.

From these data some important considerations should be made clear. The population represented in the data include principal investigators (PIs), associate researchers, postdoctoral associates, postgraduate and undergraduate students. Unfortunately, this information is not specified in the database. Still, this is something we acknowledge and it's important because researchers in our network are under different circumstances and we know that this diversity has a real impact on the structure and eventually on the dynamics of the network, as well as on the results of our model.

Our database includes the name of the project, the year it was approved for funding and the research area to which it was assigned. It specifies the names of PIs or the people responsible for the project and the names of collaborators. Researchers can be PIs in one project and collaborators on a different project. The institutional affiliation of all participants is in-

[2]SSA is the acronym for Secretariat of Health *Secretaría de Salud*; IMSS is the acronym for Social Security Mexican Institute (*Instituto Mexicano del Seguro Social*); ISSSTE stands for Institute for Social Security and Services for State Workers (*Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado*)

cluded. Through this affiliation we know the principal institution behind every project.

Even though curation and analysis work of the database is still ongoing, some relevant facts about the biomedical research can be said. Over the period of 12 years, 32 general research areas have been defined, the three most funded research areas are *chronic and degenerative diseases*, *malignant neoplasms*, and *infectious and parasitic diseases*. The least funded area is *Ethics and medicine*. The area with the most researchers is *malignant neoplasms*. Other areas of relevance for México are *diseases related to poverty* and *Health and vulnerable groups*.

From the institutions that have participated in a protocol funded by FOSISS, less than one fifth have been responsible for a project and more than 95% of them are Mexican, public institutions. There is also an important presence of foreign institutions as collaborators, most of them from the United States, though institutions from the UK, France, Spain, Netherlands, Colombia and Cuba are also in the database.

Besides the characteristics of the population there are some other boundary conditions that play an important role on the network topology and dynamics, that motivated the development of our model. Biomedical research in México constitutes a vibrant community and collaboration is part of everyday work. However, México does not have public biobanks for research purposes (which are specially relevant for research in genomics, for example), there is no regulation on the access to biological samples such as tissue, cells, DNA, RNA, etc.[3] Something similar happens with data. There have been some attempts to create open data repositories for biomedical research, but they have not been established yet. Regulation on these subjects is still missing. Finally, technology (e.g., PCR, sequencing and expression profiling technology) is in the domain of the institutions with the highest research profiles and sometimes PIs see technology as a personal good.

From our ethnographic work to date, we have been able to see that biological samples, data and technology can become instruments for negotiating collaboration. For example, among people involved in research projects, there are researchers that do not have direct access to samples, simply be-

[3]Regulation exists regarding researcher-subject relations based on legal and ethical grounds. Also, all projects need to be approved by the Ethics Committee and IRB.

cause their institution does not offer clinical services. Many of them are non medical doctors but chemists, biologists, physicists, and mathematicians. There is another group of researchers that are placed on hospitals who are able to do research and have access to biological samples from their own patients. It seems that this group is the most privileged one, and the least pressured to establish collaboration at whatever cost. Finally, there is one more group formed by those who work as clinicians at small hospitals with no research infrastructure whatsoever. This group may have an interest in research and the way for them to become part of a project and be listed as authors in scientific papers is by giving researchers who do not have access to biological samples access to patients.

Due to these differences in the access to resources, researchers in general are compelled to build strategic alliances through which samples, data, technology and authorship, among other assets, become part of a constant flow through the network. Social and political capital, as well as concentrations of resources become fundamental tools for establishing fruitful collaborations.

3 Methodology

Our model is based on the iterated version of the Prisoner's Dilemma (PD) and a coordination game instantiated on networks. Implementing games on networks is not new and it's an active area of research aimed to understand the evolution of cooperation in networks populated by selfish agents [22, 23, 24, 28, 27]. In many network models on which some of game theory games are simulated, agents' decision to cooperate or defect depend on a specific strategy, such as the well known *tit-for-tat* [25, 26]. In some other cases, agents can modify the weight of the interactions with their neighbors [27]. From a different perspective others have explored the effect of different topologies on the emergence of cooperation [28, 29]. In our case, an agent's decision to cooperate or defect is an outcome that depends on a balance between utilities and the current strength of its collaboration relationships. Such balance reflects the overall success or failure of its strategies. We study the behavior of the system under different topologies, including a real-world network.

In our model, agents are embedded in a network with varying number of neighbors. Following the traditional PD game, the strategy chosen by an agent and the strategy chosen by its neighbors will produce a pay-off. Pay-off follows the traditional PD rule: $T > R > P > S$. T is for temptation to defect. It is the highest pay-off and it takes place when the player defects and the other cooperates. R is for reward for when both players cooperate. P is the punishment for when both players defect. And S is for suckers pay-off, the worst outcome that takes place when the player cooperates but its neighbor defects. Utility is a property of agents in which pay-off is accumulated.

PD utility pay-off matrix

	Cooperate	**Defect**
Cooperate	R, R	S, T
Defect	T, S	P, P

The strength of the connection, represented by w, is a property of the link between two agents and gets updated according to an A_{ij} matrix of a coordination game. In the w matrix, the highest value goes to an edge when both agents cooperate, getting an R for reward, if one of them defects, the connection gets weaker getting P for the collaborative connection being punished. If both agents defect, the value w doesn't change, which means that agents didn't interact or that the interaction gets nullified N. In this game, the best action for any agent is to coordinate with its neighbor, either beacuse it wins or it doesn't loose.

w pay-off matrix

	Cooperate	**Defect**
Cooperate	R	P
Defect	P	N

After each game, the agent adds-up utility (u), which is the sum of the pay-offs following the PD matrix. A pair of neighbors will add-up to the strength of their connection (w_{ji}) as they coordinate or anti-coordinate, being w also cumulative. We measure global utility and connection strength for the whole network. Global utility U is the sum of all individual utilities and global strength of connections or W is the sum of every pair of agents' links w. Metaphorically, the strength of connection can be thought as some sort of "trust".

It should be noted that the same actions or behaviors work for both u and w. There are two reasons for this decision in the design of the model. The most general one is that we believe that in the real world, actions such as cooperating and defecting affect the strength of the connection among people. The second one is that we think that selfishly maximizing resources and strenghting relationships are *opposing forces* acting on the same set of behaviors. The actions of an agent imply a trade-off in which defecting may increase its utility at the expense of its collaborative relationships. If collaborators have nourished their relationships, they might be strong enough to endure occasional defection. Cooperating may build up relationships but it can be expensive for the player.

3.1 Network initialization and agent state update

All networks are initialized equally. The number of nodes for every network is 4122, the same as in the FOSISS network. The same utility is given to every agent and all edges are asigned the same weight. In the case of the FOSISS network, edge weight is given by the number of collaborations among researchers, utility remains the same for all nodes as in the other networks.

The probability for an agent to cooperate or defect depends on a number (η) that referes to a historical balance between average utility and the average strength of the connections with its neigbors. This is so because we assume that whatever the result in utility or strength of connection, as long as one of them increases, the player will be confident in the strategy followed so far.

η is calculated as:

$$\eta_i = \frac{\langle f_i \rangle + \langle w_{ij} \rangle_j}{2}$$

For the agent to decide whether to cooperate or not, η is compared to a global threshold ν. If the agents' $\eta > \nu$, then the agent will cooperate, otherwise he will be suspicious and will defect. ν is a global parameter that establishes a threshold that an agents' η must cross in order to decide to cooperate. In this way, η can limit the size of the population of cooperators. Due to what the system and the game can offer to agents in terms of utilities and the strength of collaboration relationships, η represents the carrying capacity of the system for the population of cooperators.

Our simulation was tested on an Erdös-Renyí, a Watts-Strogatz small-world and Barabási-Albert topologies, as well as on the real biomedical research collaboration network. The simulation was run in a synchronous manner, in which all agents update their behavior simultaneously.

We ran two different experiments. In the first we simulated different values of carrying capacity ν. With this experiment we were able to see how the number of cooperators, utility, strength of connections among agents and the ratio of shifting state population would change in the range of the carrying capacity. For this experiment the states of the agents were the same at initialization, for all values of the carrying capacity. Since the model is deterministic, it will return the same result if run under the same conditions.

The second experiment consisted in running the simulation under the same degree of carrying capacity ν but randomizing the initial states of the agents. This would show that the system converges to a global state. For every network, the simulation was run 100 times and results were averaged.

4 Implementation of the model in different topologies

We built three classical topologies for networks besides the FOSISS network, their parameters are shown in the following table.

Topology	m	$\langle k \rangle$	$\langle C \rangle$	$\langle l \rangle$
Erdös-Rényi	25591	12.4	0.003	3.6
Watts-Strogatz	206100	100	0.7	3.4
Barbási-Albert	183465	89	0.06	2.13
FOSISS	23391	11.39	0.87	5.49

4.1 Erdös-Renyí

Erdös-Renyí networks [30] (random networks) are constructed by randomly selecting a pair of N possible nodes and attaching them with an edge, given a probability p, as long as there is no edge between them. The result is a Poisson distribution for connectivity of nodes $P(k)$, where each node has a degree quite close to the average $\langle k \rangle$. Also for this type of network, average clustering coefficient $\langle C \rangle$ is small, actually it is equal to p (the probability of connecting two nodes) and the average shortest path length $\langle l \rangle = \frac{lnN}{ln\langle k \rangle}$.

4.2 Small-World

Watts-Strogatz networks [31] (small-world networks) are in a regime between a fully regular grid (lattice) and a random network (Erdös-Rényi). In order to build them, a node is chosen from a lattice (a ring) and the edge that connects it to nearest neighbor in a clockwise sense. With probability p, this edge is reconnected to a node chosen uniformly at random over the entire ring, with duplicate edges forbidden; otherwise the edge is left in place. This process is repeated by moving clockwise around the ring, considering each node in turn until one lap is completed. Next, the edges connect nodes to their second-nearest neighbors clockwise. And as before, each of these edges is randomly rewired with probability p, and continue this process, circulating around the ring and proceeding outward to more distant neighbors after each lap, until, each edge in the original lattice has been considered once. The main characteristic of these networks is that the average shortest path length is small and grows as $log(N)$ ($\langle l \rangle \sim log(N)$). Also, the average clustering coefficient $\langle C \rangle$ remains large in terms of p. For $p < 0.1$, $\langle C \rangle \sim 1$.

4.3 Barbási-Albert

Barbási-Albert networks [33] (scale-free networks) are generated by adding new nodes to a network. Each new node is added connecting it to an existing node with a probability proportional to the degree k (connectivity) of each node (*preferential attachment*). The result is a a power law distribution for connectivity of nodes $P(k)$ where few nodes have many connections and the most have very few connections. Furthermore these networks are also small world networks, showing a quite small $\langle l \rangle$.

4.4 FOSISS: Biomedical research community network

The biomedical research network on which we are running our model was generated with data from collaborative projects. Our data was obtained from CONACyT and includes information for twelve years of *FOSISS* grants. Data included names of Principal Investigators, collaborators, research topics, etc. The network we are using here has researchers as nodes and edges represent the connection of two scientists when they colaborate in the same project. Edges are also weighted according to the number of projects shared by any pair of scientists.

5 Results

In this section we present the main results of the study, namely the topological structure of the underlying network models, the dynamics of the games under different parameters and network topologies and the distribution of utility and of the strength of interaction resulting of playing the games in all the different scenarios considered, including the real FOSISS network.

FOSISS network summed-up a total of 145 components or subnetworks, but we ran the model on the giant component made-up of 4122 researchers, and 23391 edges. The giant component was analyzed using *Cytoscape* **Figure 1**. Results show that it is a well integrated network, with a clustering coefficient $\langle C \rangle = 0.870$, an average shortest path length of $\langle l \rangle = 5.493$ and a density of $p = 0.003$. Such properties recall a small-world topology [31], and a great deal of self-organization when compared to a random network with the same density and number of nodes. Network centralization is 0.023, since there are no visible researchers that play as hubs in the network. Nevertheless the network heterogeneity is 0.873, which means that the network is highly hierarchical. When the degree distribution is analyzed, degree decreases as a power-law with an exponent of 1.7, similar to other social networks described as scale-free topology networks [33]. Finally, the average number of neighbors of each node is 11.39 [34].

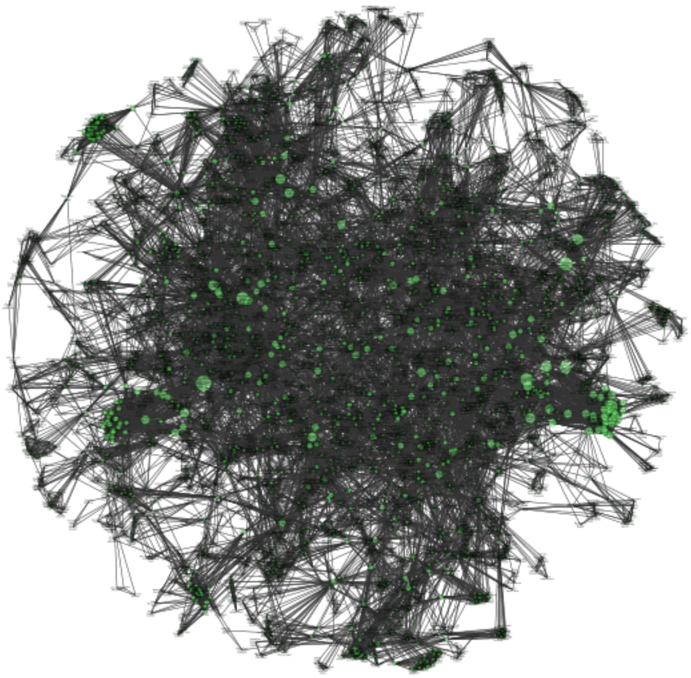


Figure 1: Bioemdical research collaboration network (FOSISS) giant component.

Other results to report are those of the dynamics of different variables as the carrying capacity ν changes. The most salient result is that for ν between 0.19 and 0.24, there is an apparent phase transition in all different topologies and for all the different variables. Nevertheless, it is worth noticing that the shape of the phase transition is different according to the topology of the network at stake. When ν is between 0.0 and 0.2, that is, when there is no space or a very short one for suspiciousness, all agents cooperate, when *carrying capacity* is above 0.25, all agents defect. *Utility*, *strength of interactions*, and *changing state population* replicate that same behavior for the same limits.

In **Figure 2**, we present how the number of cooperators in the population change as ν changes. In the Erdös-Renyí, network, between 0 and 0.18 approximately, all agents converge to a cooperative behavior, from 18 to 20, convergence to cooperative state takes longer but eventually all agents are cooperating. Close to $\nu \approx 0.21$ there is a sharp fall to a point in which around half the population is cooperating and the rest is defecting. Reaching $\nu \approx 0.25$ there is another sharp fall of cooperators and all agents turn into a defecting state.

In the case of the Watts-Strogatz, small-world network, the whole population remains cooperating for ranges between 0 and 0.2 but as it gets closer to 0.2, more time is needed for the population to become full of cooperators. In $\nu \approx 0.2$ the cooperators will represent only half of the population and such number of them will be constant up to $\nu \approx 0.25$ forming a short plateau. From $\nu \approx 0.25$ to $\nu \approx 0.6$ cooperators will be present at the beginning of the simulation but will go diminishing as time goes on. In the case of the Barabási-Albert network, crossing the threshold of $\nu \approx 0.2$, there is a sharp decrease in the number of cooperators, but stays constant over time. Such behavior is present for a very short range of ν, and before $\nu \approx 0.24$, cooperators disappear for the rest of values of ν. Finally, FOSISS network behaves similar to the other networks in that there is a fall in the number of cooperators close $\nu \approx 0.2$. Different to the other networks, FOSISS network lacks the sharp reduction of cooperators, instead this population declines smoothly and progressively; specially, when it reaches a $\nu \approx 0.25$ cooperators go decreasing in a less dramatic manner all the way to $\nu \approx 0.5$. It is also noteworthy that from $\nu = 0$ to $\nu \approx 0.5$ the number of cooperators converge to a certain amount and stays constant for the rest of the simulation.

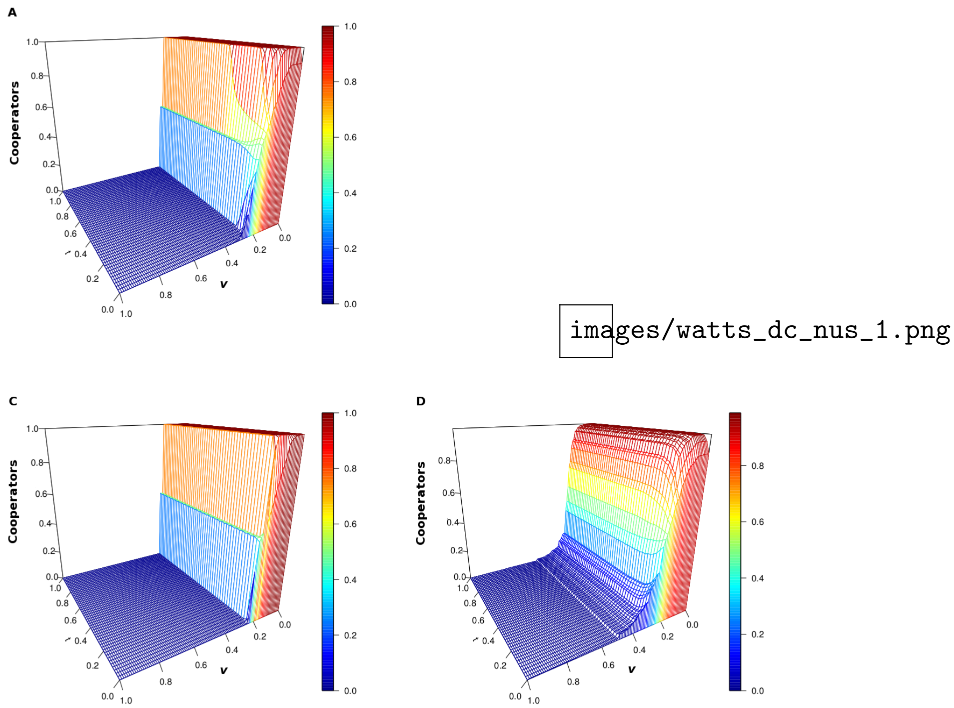
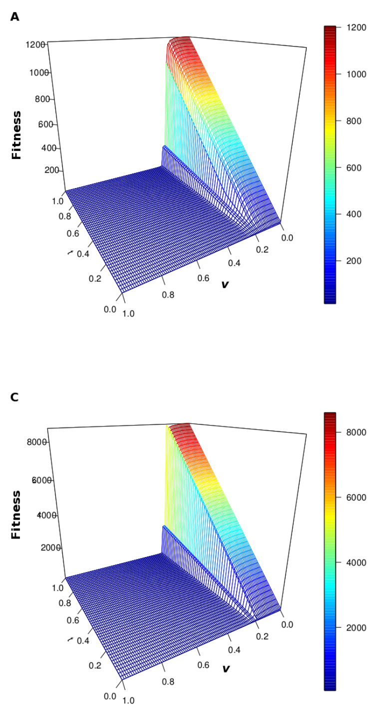


Figure 2: Proportion of cooperators as a function of carrying capacity and time.

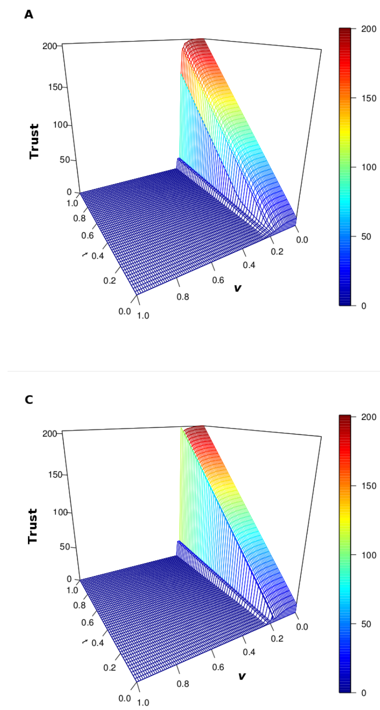
Utility and strength of interactions dynamics under different ν emulate the phase transition found before. In **Figures 3 and 4**, it can be observed that there is a drop in utility and strength of interactions according to the drop in the number of cooperators. Erdös-Renyí and Barabási-Albert networks are quite similar in the way these variables fall in two steps, the first one at $\nu \approx 0.2$ and the next one at $\nu \approx 0.23$. The fall is sharper still in the Barabási-Albert topology. Utility and strength of interactions phase transition in Watts-Strogatz network is significantly more staggered compared to the former networks. In the case of utility, there is a region in the limits of $\nu \approx 0.25$ and $\nu \approx 0.3$, before utility goes to 0, in which it remains low but stable over time. In general, strength of interactions follows the same pattern as utility but in the same $\nu \approx 0.25$ and $\nu \approx 0.3$, strength of interactions grows to a value that is higher than the one given by default but soon starts to decrease as the simulation runs. For FOSISS network, utility and strength of interactions fall is quite steep but smooth, without sharp cuts. Between $\nu \approx 0.23$ and $\nu \approx 0.28$, utility and strength of interactions start at their lowest, but there is a slight increase in both of them.



watts_fitness_nus_1.png

fosiss_fitness_nus_1.png

Figure 3: Utility U dynamics as a function of carrying capacity ν and time.

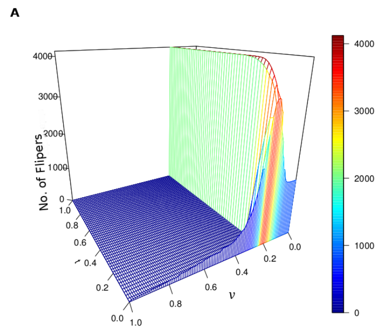


watts_trust_nus_1.png

fosiss_trust_nus_1.png

Figure 4: Strength of interactions w dynamics as a function of carrying capacity ν and time.

We also measured the number of agents shifting states –between cooperating and defecting- under different ν values. We found that for all networks there is a critical point around $\nu \approx 0.2$ in which all agents are shifting states. For Erdös-Renyí and Barabási-Albert networks, for this region, agents never settle to a single state. Contrary to the former cases, the number of shifting agents decreases considerably for the Watts-Strogatz and FOSISS networks, and find an equilibrium state. Once the the limits of this region are crossed as ν increases, the number of shifting states falls to 0 and all nodes become defectors.



watts_state_nus.png

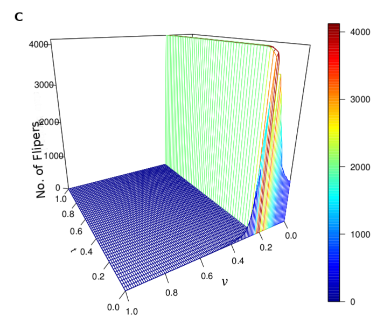


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Figure 5: Shifting population between cooperators and defectors as a function of carrying capacity ν and time.

Central to our argument is the differences in utility and strength of interactions distribution at the end of the simulation, for every topology. We found that utility distribution for the *FOSISS* network, resembles quite accurately to the distribution of utility in the Barabási-Albert network.

The distribution of utility on each topology is induced by the degree distribution. This is so, since a given agent (node) will interact with its neighbors to either cooperate or defect, in such a way that connectivity influences the number of events played and thus the likelihood of increasing its corresponding utility. For instance, utility distribution in the random, Erdös-Rényi network displays a normal-like curve. The algorithm that generates this kind of topology, assigns to every node the same probability of connecting with any other node, which produces a *poissonian* degree distribution [30]. Since the Watts-Strogatz degree distribution is described by a function that is midways between a random distribution and a scale-free network [32] one may expect also an intermediate behavior of the utility distribution. This assumption seems to be fulfilled by the distribution in Figure 6B.

The resemblance of the degree-distribution and utility distribution also holds for the Barábasi-Albert network. As mentioned in the methods section, the degree distribution of a Barábasi-Albert topology follows a power-law that describes the fact that there are a small number of nodes with large k and most nodes have a small k [33]. As it is shown in the following figure, most utility is concentrated in a few number of agents, while most agents have a small amount of it. This is consistent with other research in which concentration of resources, fame or citations in science decreases as a power-law [37, 38, 39]. FOSISS network utility distribution is also skewed to the left, similar to that of the Barabási-Albert network.

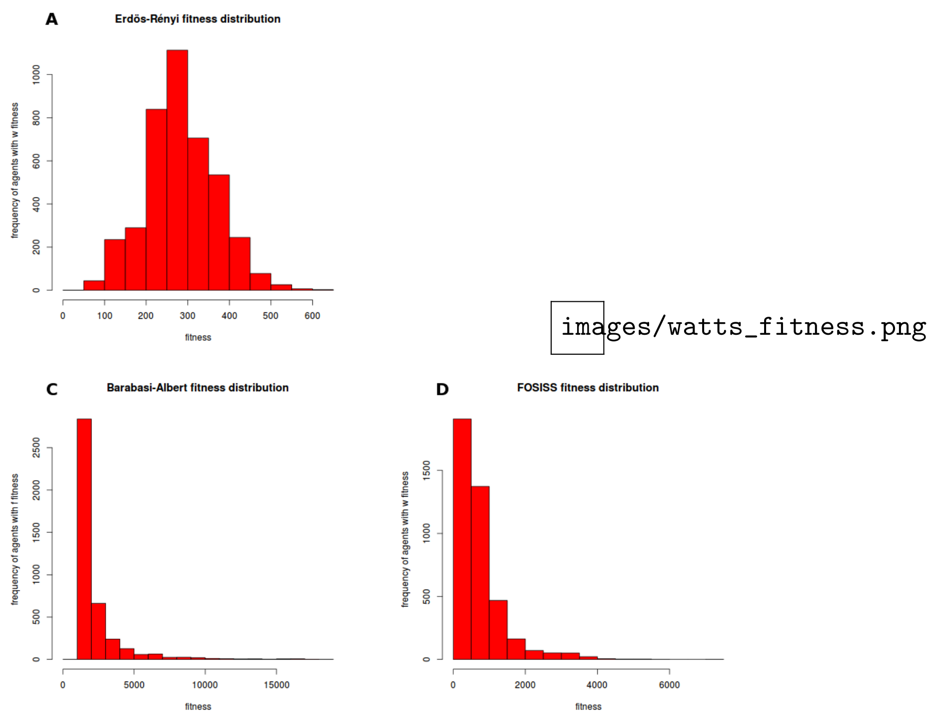

Figure 6: Utility distribution on different topologies. A. Random, Erdös-Rényi network displays a normal-like distribution. B. Watts-Strogatz network utility distribution is highly skewed to the right. C. Barabási-Albert network. Utility is distributed highly skewed to the left. D. FOSISS, biomedical researchers collaboration network distribution of utility resembles to Barabási-Albert network.

Regarding strength of interactions distribution, the Erdös-Rényi random network displays a normal distribution of strength of interactions, as expected. Again strength of interactions values are highly influenced by the corresponding degree distribution (Figure 7A). However, in the Watts-Strogatz network topology (Figure 7B), the strength of interactions distribution is a highly asymmetric bimodal, with a really-low frequency mode of low strength of interactions and a highly probability mode for high strength of interactions. A possible explanation for this phenomenon is that under network topologies maximizing inter-node communication (by minimizing the average distance between nodes) such as the Watts-Strogatz, strength of interactions is favored both among the cooperators (constituting the majority of players) and the defectors.

The Barabási-Albert network (7C) presents also a symmetric unimodal distribution with values higher (on average) than those of the Erdös-Rényi random network, this may be the effect of increased communication due to more efficient network navigability. Interestingly, the network corresponding to the real FOSISS collaborations (7D) is an asymmetric unimodal distribution in which moderate to high values of strength of interactions are more likely. We hypothesize that this effect is also due to the communication properties of the network.

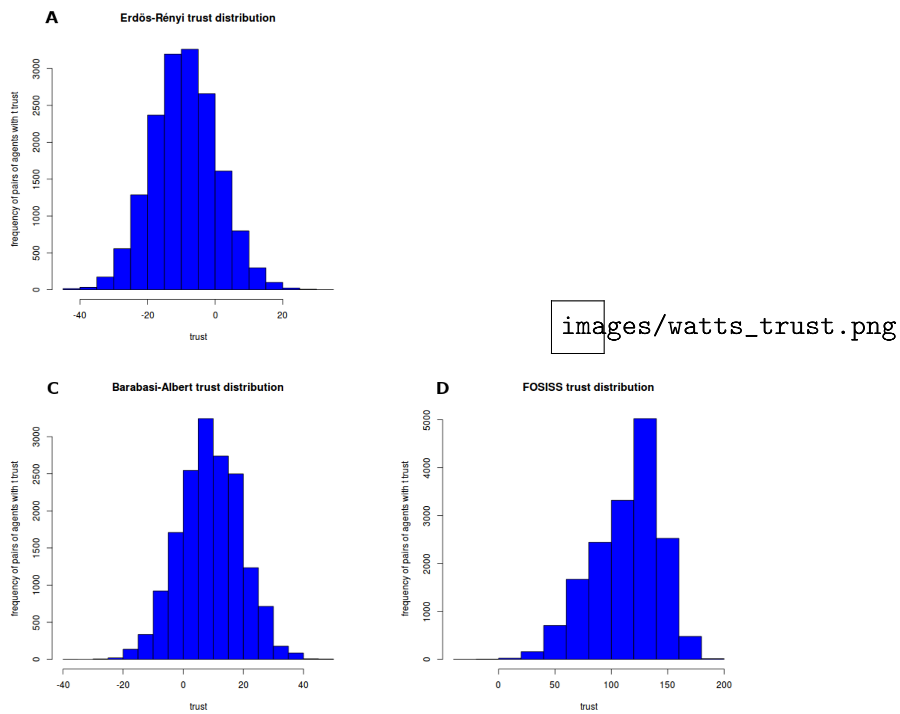

Figure 7: Strength of interactions distribution on different topologies. A. Random, Erdös-Rényi network displays a normal-like distribution. B. Watts-Strogatz network strength of interactions distribution is bimodal and highly skewed to the right. C. Barabási-Albert network strength of interactions distribution is also a normal-like curve. D. FOSISS, biomedical researchers collaboration network distribution of strength of interactions is skewed to the right.

An interesting feature of highly communicated networks (characterized by high values of clustering coefficient) is the fact that certainty among players seems to be enhanced, that is, in such networks the rate of change of strategy is significantly lower (and smoother) than in poorly connected networks. This is another instance in which easier communication (i.e. lower average minimum path lengths) lead to better performance of the whole collaborative research system.

6 Discussion and Conclusions

In this work we have analyzed the influence of parameters given by the underlying social structure of a science collaborative network on collective strength of interactions and utility dynamical behavior, based on a class of iterated PD and coordination games. Such parameters include mainly local and global connectivity like the degree centrality and average clustering coefficient, as well as communication patterns.

Under the assumptions given by the model, we were able to notice that, in general, communication within the social collaborative networks has a positive correlation with average strength of interactions between the individuals partaking in the games and also with the global collective utility (given by the sum of the individual payoffs). The better the communication among players, the higher the strength of interactions and the utility leading to an optimized functioning of the whole *scientific collaboration system*. This is an important result that may be useful for scientific policy planning and may set a foundation for the optimal use of social networks in scientific collaboration as a means to improve the relationships among collaborating peers and thus ultimately the performance of research systems. We obviously need more qualitative work in order to validate these results from a sociological and anthropological perspective.

To close this article, we would like to comment on three issues we consider important. The first one is about confronting our results with data available to us from the biomedical research community. Second, some remarks we believe are important about the role of computational simulations in the social sciences. Finally we would like to comment on our future work.

The two main results of our model are the smoothness in the phase transition-like behavior for different parameters and the distribution of utility and strength of interactions in the FOSISS network compared to other networks and their topologies. We are certain that the particular structure of FOSISS network is playing a central role in the results and because of that we would like to discuss it a little bit further.

FOSISS network is higly hierarchical according to its heterogeneity of 0.873. Because of it, one would expect to find the presence of important hubs [35], that is, a few researchers control the whole network, as has been reported in some other places [36]. Surprisingly, FOSISS network centralization is very low 0.023, i.e. there are no researchers that centralize the majority of connections. Our guess is that the network is composed of many small communities or groups with a central researcher or Principal Investigator (PI). If this is the case in the FOSISS network, it means that those groups have a very hierarchic structure as well.

Under such structure, when the clustering coefficient is considered, it can be said that groups are also well connected but that inter-group connections are sparse. In other words, individual groups are strongly connected but the network as a whole is supported by a small number of links. We came by this idea partially from another study about scientific collaborations based on co-authorships in one of the research centers that is part of the FOSISS network [10]. In the cited reference an apparently well integrated community was found (high clustering coefficient and a very short characteristic path length). Such integration was mostly superficial, since it depended on the presence of external collaborators from other research institutions (most of them from overseas). Removing these external collaborators broke down the network into small subgraphs that worked independently. Remarkably those subgraphs corresponded to the real groups of that research center. What is more, several groups had a hierarchical structure as the one we suspect is common in FOSISS subgraphs. The results showed that collaboration was poor between groups but strong among the members of each group, and that collaboration among groups doesn't emerge bottom-up, instead it seems to be promoted from the top, from the administrative authorities.

We believe that the the situation just refered is also true for the whole biomedical research community in México. The amount of PIs who have also been collaborators in other projects is about one fifth of the total number of participants. This is a number big enough to connect the whole network in one giant component. Yet, due to the topological characteristics of the

FOSISS network, it appears to be the case that researchers can be the leaders in one project and collaborators of different project of *its own research group*. CONACyT's funding policies makes it impossible for a researcher to get a grant from a fund if that researcher has an ongoing project with a grant from that same fund. That is, a researcher can ask for a grant from FOSISS if and only if at the moment he doesn't have a grant from FOSISS already. This policy has lead researchers from the same group to ask for grants from the same fund in order to rise their budgets. A consequence of this behavior is that group interactions get reinforced, but integroup connections not necessarily so.

As is common among scientific communities in biomedical research, PIs play a central role in the network. Strong PIs and well connected groups seem to be somehow responsible for the high levels of strength of interactions and the centralization of utility in our simulation. As for what seems to be phase transitions, in the case of FOSISS networks, these are smoother than those in the other networks with different topologies, even for those with a small-world topology. We think that this behavior is also the result of the hierarchical structure already mentioned. If this is true, strength of interactions is first lost in the edges that link diffrent goups and then in the edges that connect members of the groups. Connections between groups would not be as dense as those inside the groups, which means that there would not be enough information of the behavior of one group regarding its neighbors to constrain them as it seems to happen with individual researchers inside their communities. Nevertheless, if values of the carrying capacity ν keep increasing and it becomes more difficult to strengthen interactions, then strength of interactions begins to diminish inside groups.

Another issue that we would like to mention about FOSISS network topology is that it is not a robust collaboration network. At the level of groups, these might be well connected and consolidated but at the level of the network, this could be no more than an aggregate of individual groups. A robust network would be resistant to changes in the connections between groups but in the case of FOSISS, it seems that the network would brake down into small research groups by cutting some edges, as it happened in our co-authorship collaboration network [10]. The lack of robustness might be indicative of the fact that resources stay inside the groups, that is, they do not circulate through or articulate different communities. For example, one may think of certain expensive technologies for genomic research that could be bought once and shared among research groups, however, this doesn't seem to happen very often. There are some other consequences, such as low communication among groups, atomization of practices and know-hows, redundancy in equipment tenancy, difficulties for implementing community-wide infrastructures such as biobanks, etc.

On these grounds, part of our future work is based on some of the results presented here. We would like to identify researchers in our simulations and corroborate their situation in the model and in the real world. We are also interested in going back to the field and interviewing those groups with an interesting behavior found in our simulations, probably we would follow a similar strategy as the one developed in [42]. Finding communities beyond the level of the groups is an important task. We think that there are many possibilities that emerge from the integration of different methodologies. Moreover, studying social processes in science is particularly attractive due to the amounts of data already available that can be easily collected. This is a privilege because simulations can be designed on real world data, something that only very recently has become possible [43].

No doubt, social sciences are getting more "computational". This can be seen everywhere, but curiously enough, disciplines like physicis and computer science are the ones who are moving towards the social sciences and not so much the other way around. It might be the case that the pioneering disciplines in the computational social sciences will set the agenda, an agenda that will apparently be mostly based on taking advantage of big data and on hypothesis-free approaches. We believe that the social sciences have important questions that should be added to that agenda and those questions may not be answered only by big data techniques but they may require creating models and simulations in the style of the best hypothesis-driven research.

7 acknowledgements

The authors gratefully acknowledge support by grants: CB-222220-R/2013 and CB-179431/2012 (Consejo Nacional de Ciencia y Tecnología). We would also like to acknowledge CONACyT for letting us access their database. Finally, we acknowledge the help of Francisco Allende for his work curating databases of researchers.

References

[1] Vermeulen, Nikki; Parker, John N & Penders, Bart, Understanding life together: A brief history of collaboration in biology, *Endeavour*, 37(3): 162-171 (2013)

[2] Knorr-Cetina, Karol; *Epistemic cultures: how the sciences make knowledge*, MIT Press, Cambridge, MA (1999)

[3] Strasser, B.J. Collecting and Experimenting: The Moral Economies of Biological Research, 1960s-1980s. *Preprint no. 310.* Berlin: Max Planck Institute for the History of Science, (2006)

[4] Müller-Wille, S. & Charmantier. I. Natural history and information overload: The case of Linnaeus. *Studies in History and Philosophy of Biological and Biomedical Sciences.* 43:4-15, (2012)

[5] Strasser, BJ. Data-driven sciences: From wonder cabinets to electronic databases. *Studies in History and Philosophy of Biological and Biomedical Sciences* 43:85-87, (2012)

[6] Sonnenwald, DH. Scientific Collaborations. *Annual Review of Information Science and Technology*, 41.

[7] Newman, MEJ. Clustering and preferential attachment in growing networks. *Physical Review E*, 64:025102-1/025102-4, (2001)

[8] Newman, MEJ. Coauthorship networks and patterns of scientific collaboration. *PNAS*, 101, no. suppl 1, 5200-5205 (2004)

[9] Elango, B. & Rajendran, J. Authorship Trends and Collaboration Pattern in the Marine Sciences Literature: A Scientometric Study. *International Journal of Information Dissemination and Technology*, 2(3), 166-169, (2012)

[10] Hernández-Lemus, Enrique & Siqueiros-García JM, Information theoretical methods for complex network structure reconstruction. *Complex Adaptive Systems Modeling.* 1: 8, doi:10.1186/2194-3206-1-8 (2013).

[11] Gilbert, N. A Simulation of the Structure of Academic Science. *Sociological Research Online*, 2(2) 3, http://www.socresonline.org.uk/2/2/3.html

[12] Edmonds, B., Gilbert, N., Ahrweiler, P., & Scharnhorst, A. Simulating the Social Processes of Science. *Journal of Artificial Societies and Social Simulation*, 14(4) 14, http://www.jasss.soc.surrey.ac.uk/14/4/14.html

[13] Hara, N. Solomon, P. Kim SL. Sonnenwald DH. An Emerging View of Scientific Collaboration: Scientists Perspectives on Collaboration and Factors that Impact Collaboration. *Journal of the American Society for Information Science and Technology*, 54(10):952965, (2003)

[14] Lieberman, E. Hauert, C. & Nowak, MA. Evolutionary Dynamics on Graphs. Nature, 433, doi:0.1038/nature03204 (2005).

[15] Lo, T.S., Chan, H.Y., Hui, P.M., Johnson, N.F., Theory of networked minority games based on strategy pattern dynamics, *Physical Review E* 70, 056012 (2004)

[16] Buesser, P. and Tomassini, M., Evolution of cooperation on spatially embedded networks, *Physical Review E* 86, 066107 (2012)

[17] Ichinose, G., Tenguishi, Y., and Tanizawa, T., Robustness of cooperation on scale-free networks under continuous topological change, *Physical Review E* 88, 052808 (2013)

[18] Ahmed, A., Karlapalem, K., Inequity aversion and the evolution of cooperation, *Physical Review E* 89, 022802, (2014)

[19] Vilone, D., Ramasco, J.J., Sánchez, A., San Miguel, M., Social imitation versus strategic choice, or consensus versus cooperation, in the networked Prisoners Dilemma, *Physical Review E* 90, 022810, (2014)

[20] Wardil, L., Hauert, C., Cooperation and coauthorship in scientific publishing, Physical Review E 91, 012825, (2015)

[21] Hanauske, M., Evolutionary Game Theory and Complex Networks of Scientific Information, in A. Scharnhorst et al. (eds.), *Models of Science Dynamics, Understanding Complex Systems Series*, Springer Berlin Heidelberg, (2012)

[22] Szabó, György & Fáth, Gábor, Evolutionary games on graphs. *Physics Reports*, 446: 97-216 (2007)

[23] Nowak, Martin A. & May, Robert M, Evolutionary Games and Spatial Chaos. *Nature*, 359: 826-829, (1992)

[24] Oshtuki, Hisashi, Hauert, Christoph, Lieberman, Erez & Nowak, Martin A, A simple rule for the evolution of cooperation on social graphs. *Nature*, 441: 502-505 (2006)

[25] Axelrod, Robert, *Evolution of cooperation: Revised edition*, Basic Books, Cambridge, MA (2006)

[26] Nowak, Martin A. & Highfield, Roger, *Supercooperators. Altruism, Evolution, and Why We Need Each Other to Succeed.* Free Press, New York, NY (2011)

[27] Santos, Francisco C., Pacheco, Jorge M., Lenaerts, Tom, Cooperation prevails when individuals adjust their social ties. *PLoS Computational Biology*. 2(10): 1284-1291 (2006)

[28] Santos, F.C. & Pacheco, J.M., Scale-Free Networks Provide a Unifying Framework for the Emergence of Cooperation. *PRL*, 95: 098104-1 to 098104-4, (2005)

[29] Hauert, Christoph & Doebeli, Michael, Spatial structure often inhibits the evolution of cooperation in the snowdrift game. *Nature*, 428: 643-646, (2004)

[30] Erdös, P. & Renyí, A. On Random Graphs. *Publ. Math*, 6:290 (1959).

[31] Watts, Duncan J. & Strogatz, Steven H, Collective dynamics of 'small-world' networks. *Nature*, 393: 440-442 (1998)

[32] Barrat, A.; Weigt, M., On the properties of small-world network models, *European Physical Journal B* 13 (3): 547560, (2000)

[33] Barabási, Albert-László. & Albert, Réka, Emergence of Scaling in Random Networks. *Science*, 286: 509-512 (1999)

[34] Shannon P, Markiel A, Ozier O, Baliga NS, Wang JT, Ramage D, Amin N, Schwikowski B, Ideker T. Cytoscape: a software environment for integrated models of biomolecular interaction networks. *Genome Research*, 13(11):2498-504, (2003)

[35] Jun Wu, Yue-Jin Tan, Hong-Zhong Deng, Da-Zhi Zhu. A new measure of heterogeneity of complex networks based on degree sequence. Eds. Ali Minai, Dan Braha, Yaneer Bar-Yam *Unifying Themes in Complex Systems. Proceedings of the Sixth International Conference on Complex Systems*, Springer Berlin Heidelberg, 66-73, (2008)

[36] Yousefi-Nooraie R, Akbari-Kamrani M, Hanneman RA, Etemadi A. Association between co-authorship network and scientific productivity and impact indicators in academic medical research centers: A case study in Iran. *Health Research Policy and Systems* 6:9 (2008) doi:10.1186/1478-4505-6-9.

[37] Simon, HA. On a class of skew distribution functions. *Biometrika*, 42 (3-4): 425-440, (1955)

[38] Price, Derek JS. Networks of Scientific Papers. *Science*, 149(3683): 510-515, (1965)

[39] Merton, Robert K, The Matthew Effect in Science, *Science*, 159(3810): 56-63 (1968)

[40] Epstein JM & Axtell R. *Growing artificial societies. Social science from the bottom up.* The Brookings Institution Press and The MIT Press, Washington, DC. (1996)

[41] Lansing JS. "Artificial Societies" and the Social Sciences. *Artificial Life*, 8:279-292, (2002)

[42] Hara N, Solomon P, Kim SL, Sonnenwald DH. An emerging view of scientific collaboration: Scientists' perspectives on collaboration and factors that impact collaboration. Journal of the American Society for Information Science and Technology, 54(10):952965, 2003

[43] Barabási, AL. The network takeover. *Nature*, 8:1416, (2012)

[44] Conte R, Gilbert N, Bonelli G, Cioffi-Revilla C, Deffuant G, Kertesz J, Loreto V, Moat S, Nadal J.-P, Sanchez A, Nowak A, Flache A, San Miguel M, Helbing D. Manifesto of computational social science. *The European Physical Journal, Special Topics* 214(1):325346, (2012)