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**CENTRO DE DESENVOLVIMENTO E PLANEJAMENTO REGIONAL**

# THE EMERGENCE OF A GLOBAL INNOVATION SYSTEM: AN INTER-TEMPORAL ANALYSIS THROUGH A NETWORK OF NETWORKS[*]

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**SUMÁRIO**

**ABSTRACT**

This paper investigates a structural change: the emergence of a Global Innovation System (GIS). Focusing on international knowledge flows (IKFs) we organize the network in three layers according to the type of IKF that connects the institutions: scientific collaboration, patent citation or article citation in patents. We investigate how those three layers overlap and entangle, figuring out a network of networks. We found that each layer follows a free-scale network structure associated with a self-organized system and creates an intrinsic hierarchy. The subnetwork that connects the three layers is also a free-scale network. The intertemporal analysis shows that those properties persist from 2009 to 2017.Therefore, we identified a complex network structure that is very unlike being created by a random process. This structure shows hierarchy, association with self-organized systems, robustness, and specialization, which are the fundamental aspects necessary to define a system. In the context of this analysis, that is the Global Innovation System.

*Key-Words*: International knowledge flows; Innovation systems; Networks of networks

*Jel Classification*: O32, O34, O39

**RESUMO**

Este artigo investiga uma mudança estrutural: o surgimento de um Sistema Global de Inovação (GIS). Com foco nos fluxos internacionais de conhecimento (IKFs) organizamos a rede em três camadas de acordo com o tipo de IKF que conecta as instituições: colaboração científica, citação de patente ou citação de artigo em patentes. Investigamos como essas três camadas se sobrepõem e se entrelaçam, descobrindo uma rede de redes. Descobrimos que cada camada segue uma estrutura de rede sem escala associada a um sistema auto-organizado e cria uma hierarquia. A sub-rede que conecta as três camadas também é uma rede sem escala. A análise intertemporal mostra que essas propriedades persistem de 2009 a 2017.Portanto, identificamos uma estrutura de rede complexa, certamente não criada por um processo aleatório. Essa estrutura mostra hierarquia, associação com sistemas auto-organizados, robustez e especialização, que são os aspectos fundamentais necessários para definir um sistema. No contexto desta análise, esse é o Sistema Global de Inovação.

*Palavras-Chave*: Fluxos internacionais de conhecimento; Sistemas de inovação; Rede das redes

*Classificação Jel*: O32, O34, O39

## INTRODUCTION

This paper investigates a structural change in the current economic system: the emergence of a Global Innovation System (GIS). Researchers from many different backgrounds have investigated this structural change – Binz and Truffer (2017) present a broad literature review on this topic.

Our research investigates this structural change by focusing on international knowledge flows (IKFs). To integrate this investigation with the previous literature on national innovation systems (NISs), we investigate international knowledge flows connecting institutions (firms, universities, research institutes, hospitals) from different NSIs. Among possible IKFs types, we focus on those created by patent citations - of other patents or scientific articles - and scientific co-authorships. We have been amassing data on those flows, leading us to investigate how IKFs create a global layer connecting several NISs that has a specific dynamic, being part of the emergence of a GIS. The growth and consolidation of this global layer in innovation systems are references for understanding the emergence of GISs as a four-stage process (Britto et al., 2021b), as they change the whole system and create a new hierarchy among innovation systems and their different levels – local, regional, sectoral, and now international.

We represent the institutions and the IKFs they create as networks where the nodes are the institutions and the links connecting these nodes are the IKFs. We organize the network in three layers according to the type of IKF that connects the institutions: scientific collaboration, patent citation or article citation in patents. Firstly, we analyze each of those layers singly (Ribeiro et al., 2014, Britto et al., 2021a, Ribeiro et al., 2018) to identify their structure and organization. We find evidence of their relation to self-organized systems, components of complex systems.

Then we investigate how those three layers overlap and entangle, figuring out a network of networks (Ribeiro et al., 2022). Again, there is evidence of this network of networks (NoN) relation with self-organized systems.

Finally, this paper moves to an intertemporal analysis, investigating those three layers' structure and their entanglement for 2009, 2012, 2015 and 2017. Table 1 presents the general data for each year. The international knowledge links grew from 2,022,615 in 2009 to 17,240,862 in 2017, whereas each layer grew under apparently different dynamics.

**TABLE**
**Data On The Three Layers – International Knowledge Links By Layer And Their Total (2009, 2012, 2015 and 2017)**

| Year | LAYER #1: Scientific international co-authorships | LAYER #2: International patent citations of scientific articles | LAYER #3: International patent citations of patents | TOTAL of International Knowledge Links |
|---|---|---|---|---|
| 2009 | 1,646,786 | 6,326 | 369,503 | 2,022,615 |
| 2012 | 7,317,107 | 59,652 | 729,598 | 8,106,357 |
| 2015 | 7,083,075 | 118,571 | 1,120,228 | 8,321,874 |
| 2017 | 15,920,875 | 70,667 | 1,249,320 | 17,240,862 |

Source: WebOfScience, Patstat - authors' elaboration

The growth and consolidation of these international layers support our suggestion that we may be in the third stage of GIS formation (Britto et al., 2021b, pp. 270-273). Ribeiro et al. (2022) present a snapshot of the three layers in 2017 and their overlapping and entanglement. With the new data shown in Table 1, our research investigates the following issues:

1. How the entanglement among the three layers evolves.
2. The main question of his paper: is there a specific dynamic for the subnetwork that connects the three layers, i.e. the connections that turn the layers into a network of networks?

After this analysis, we return to our theoretical framework, asking how those empirical findings and answers contribute to our analysis of the emergence of a GIS.

We organized this paper into five sections. The first present our theoretical background. The second discusses networks and their dynamics. The third deals with data and methodology. The fourth analyses the data and the three network layers, investigating their evolution and entanglement dynamics among them. The fifth discusses how those findings improve our understanding of an emerging GIS.

## 1. GIS: A THEORETICAL BACKGROUND

### 1.1. A Dynamic Process leading to GIS

Science and technology are planetary by definition. Since immemorial times knowledge has travelled across regions, continents (Diamond, 2017) and, very lately, across empires and countries (Needham, Mokyr).

We may exemplify those travels of technology by a list prepared by Needham (1954, p. 242) showing how different technologies originated in China and migrated to the West until 1300. Mokyr (1990, p. 44) mentioned the West's completion of catch-up around the 13th century, when the West had absorbed the knowledge that originated in the East.

Those planetary travels of knowledge passed through fundamental changes historically as institutional developments took place. We can summarize the logic behind those changes as an institutionalization of science and technology travels and exchanges between different regions, peoples and nations.

The Industrial Revolution may be a dividing line. There is an extended international transfer of knowledge, especially from India to the West, in general, and Britain, in particular, that prepared the basis of the substitution of imports process. This process culminated with the new revolutionary technologies to produce textiles – Beckert (2014, p.32-35) describes the extended absorption of Indian products of cotton textiles, first conquering markets in Europe. Remember that India was the "textile manufacture workshop of the world" in the 18th Century (Darwin, 2007, p. 193).

This extended learning and assimilation processes – international knowledge flows through copies, imports, travels to learn and industrial espionage (Beckert, 2014, pp. 49-50) - culminating in the Industrial Revolution brought notable changes, with the beginning of a modern industrial capitalist era. This "great transformation" (Polanyi, 1944) generated institutional changes in the relationship between science and technology, described by Marx (1867, p. 48) as the rise of the "systematic application of science to technology". Rosenberg (1976, pp. 126-138) analyses this institutional transformation.

Rosenberg (1982, pp. 141-159) evaluates the transformation in the relationship between science and technology. A detailed description of how the institutionalization of science, the generation of technology by firms and the various feedbacks among them signalized a new era. Further, the neo-Schumpeterian elaboration on national innovation systems captured that new era (Freeman, 1982). The UK innovation system led this process. Braudel (1986, chapter 6) and Landes (1969, chapter 2) are references for descriptions of institutions of that early NIS.

The propagation of the industrial revolution towards other countries, which compose the current capitalist center as the USA, Germany, and Japan, is a history of international knowledge flows in the 19th century supporting the formation of their NISs. Rosenberg (1972, chapter 3) describes how America was an imitator country during the first half of the 19th century and how the technological flows between America and Europe began to change their directions in the last decades of that century. Mowery and Rosenberg (1993, p. 31) explain the "ability of the United States to exploit foreign sources of knowledge". Keck (1993, pp. 116-117), investigating the German NSI, shows how British and Belgian were essential for "new machinery and for skilled workers to bring advanced technology to its industries". Odagiri and Goto highlight the hiring of British teachers to begin higher education in Engineering in Japan (1993, p. 79) and in three case studies – steel, electricity, and automobiles – trace the contribution of foreign knowledge to their beginnings (pp. 116-117).

Therefore, the formation of national innovation systems, in developed and non-developed countries, from the 19th to the 20th centuries involved international knowledge flows – now more institutionally organized than earlier. International flows are a precondition for the formation of NSIs. Once a structural change in modern capitalism consolidated, countries with organized NISs started a new process, as those national innovation systems began to be connected internationally by particular flows and institutions. We can point to the insertion of NSIs in the international scenario as a feature that differentiates them.

Those international connections between different national innovation systems created a new process: the formation of a GIS. Britto et al. (2021b) discuss this process as a four-stage one that we based our theoretical elaboration on because this process is an expression of evolutionary dynamics typical of complex systems. In complex systems, a change in one part reverberates through the whole system transforming it globally.

The first stage of GIS-formation – "national systems of innovation and their international connectors" - may be related to an institutional framework located by the 1880s: "an institutional arrangement, of national systems of innovation centered around domestic firms, with domestic operations and serving mainly their domestic markets, connected to other national economies through export and import of goods, emigration and international travels to promote learning, sending and/or receiving researchers and students to/from abroad". (Britto et al., 2021b, p. 271). Crawford (1992) argues that the Nobel Prize's institutionalization is an essential change for a new phase of internationalism in science.

The second stage of GIS formation – "national systems of innovation and the beginning of a global layer of international flows" - expresses the initial formation of a global layer of international flows, related to the transformation of the typical firm of capitalism into a transnational firm, a firm with a "global view" (Hymer, 1970, p. 443). The beginning of an international division of innovative activities within emerging transnational firms may be related to those global flows created by those firms (Dunning and Lundan, 2008, pp. 215-223). During this phase, the beginning of the more formalized international scientific collaboration also contributed to the global layer. This global layer began to change the dynamic of different NSIs connected by it.

The third stage – "consolidation of a global layer of international connections and a new hierarchy of innovation systems" – is a consequence of a new combination of the three driving trends pushing the formation of global innovation systems. The first is a new phase in the internationalization of innovative activities of TNCs (Dunning and Lundan, 2008, pp. 189-196). The second is a new technological revolution that changed Information and Communication Technologies (TICs), opening room for an intensification of cross-border knowledge flows. The third is a consequence of the growth of scientific communities in several countries, either developed or non-developed, intensified the internationalization of science. This trend has been strengthened by the emergence of challenges on a global scale, such as those arising from climate change and, more recently, from the coordinated fight against pandemics. Those driving trends led to the growth and consolidation of different layers of global knowledge flows. Given the different roles played by institutions in those flows, the formation of nodes with particular positions in those layers probably triggered a new process involving the overlapping and entanglement of different NSIs. As presented in the introduction, we conjecture that we are in this stage now.

The fourth stage – "global innovation system" – probably will be characterized by solid international institutions articulating the whole system and this international dimension – now institutionally organized as such – as the primary source of dynamics in a more globalized economy.

We investigate this four-stage process by identifying the organization and growth of the IKFs created by it. As mentioned in the introduction, this paper focuses on analyzing the knowledge flow between institutions from different countries – the IKFs – that are our unit of analysis. Thus, identifying the dynamics of those IKFs, represented by network links, became our strategy for investigating the changes within the process of GIS formation.

### 1.2. Institutions of GIS and IKFs

As we are in the third stage of GIS's formation, it is important to look closer to the institutions that have already formed it to understand better our research strategy and the meaning of the layers we empirically evaluate.

Binz and Truffer (2017) organize a multi-scalar interpretation of innovation systems and articulation of different levels – global, transnational, national and regional. Binz and Truffer (2017, Figure 1) present a "hypothetical global innovation system in healthcare". At that level, only international institutions are present – TNCs, International NGOs, International consultancies, international research institutes and international institutions like the WHO

Driving the emergence of a GIS, there are transnational corporations (TNCs). Truly international institutions, they are key institutions of this level of innovation systems – coherent with the elaboration on national innovation systems that placed firms as the key institutions (Edquist, 2005). TNCs previously have connected and tensioned innovation systems (Silva, 2014) and now they create a new level in those systems. As Cantwell (2009) puts forward, they have become truly global systems. As they reach this level of international organizations, they are essential players in turning global capitalism into a complex system. Their operation depends upon and creates new global knowledge flows, as Ivarsson and Alvstam (2005) show.

Universities and research institutes, which constitutes fundamental institutions of national innovation systems, are solid and well-connected enough to consolidate multiple forms of international knowledge flows, starting from students and scientists sent abroad (Geuna, 2015) until very consolidated research networks (Graf and Kalthaus, 2018) and even to explicit mentions to global science (Wagner, 2019; Edler et al., 2011). Leading universities strongly connects themselves to international networks (Ribeiro et al., 2018, p. 169), and now there are new initiatives to explicitly international networked research ventures within universities (Kolesnikov et al., 2019)

In this context, other essential institutions are the internationals like the WHO that Binz and Truffer (2017, Figure 1) identifies as a component of a "hypothetical global innovation system in healthcare". International institutions play an increasing role in accelerating global collaboration and their consequent knowledge flows (see Corbera et al., 2016, for IPCC).

Also, as an inductor of IKFs, international conferences are institutional places to organize face-to-face interactions between people involved in science and technology. The total USA-addressed papers published in WoS from conferences and meetings reached 272,285 in 2017 (29.63% of the total of WoS USA-addressed papers). In those conferences, authors of papers may meet patent inventors or at least both may follow what are being produced in different sectors.[1]

[1] This could be a line of investigation, based on possible matches between patent inventors and scientific papers authors participating in the same conferences Two examples illustrate this conjecture. First, for patents citing cross-border patents: see USPTO 7,924,913 citing USPTO 6,463,445 and the paper "New standardized extensions of MPEG4-AVC/H.264 for professional-quality video applications" published as one 2007 IEEE INTERNATIONAL CONFERENCE ON IMAGE PROCESSING paper – two co-authors of this Conference paper (Sullivan and Suzuki) are patent inventors of the citing and the cited patents, respectively. Second, for patents citing scientific papers: see USPTO 11,354,484, citing articles from the Proceedings of SPIE, volumes 9,048 and 101,143 – one patent inventor, Steven Hansen, has a paper in that same issue – therefore, he might have attended sessions where the papers he cited were presented.

Given those international flows connecting firms and universities, the interactions of those two essential institutions of innovation systems assume an important cross-border dimension, multiplying the possible avenues of those relationships.

At a sectoral level, the level of internationalization of innovation systems is so intense that studies of sectoral innovation systems are among the pioneers of the elaboration on GIS. Some authors such as Graf and Kalthaus (2018), Engels and Ruschenburg (2008), Binz and Truffer (2017; 2020) and Hipp and Binz (2020) have investigated the broad sector related to clean energies in this regard. Other sectors that might be advanced in those international connections are pharmaceutics (see Cantner and Rake, 2014). From other theoretical backgrounds, there are investigations of specific products such as Ipods (Linden et al., 2007).

Since the initial elaboration on these sectoral innovation systems, some authors have perceived the role of the international dimension in them (Malerba, 2004, pp. 479-481).

Mobility of researchers, scientists, engineers and entrepreneurs has been, as seen in sub-section 1.1, a relevant knowledge flow. Recent investigations point to the intensification of those flows. Since the consolidation of innovation systems, mobility and migrations, as IKFs, open new opportunities and new directions of those flows, as there are both "brain drain" and "brain gain", new avenues for learning, interaction and strengthening of national innovation systems (Breschi et al., 2020; Gibson et al., 2014; Liu and Buck, 2007, Saxenian, 2006; Ferrucci, 2020). Mobility supposes that someone trained in one institution moves to another abroad, so at least two national innovation systems are involved.

The emergence of global problems - such as the risk of climate change and the deterioration of biomes - also reinforces the importance of international institutions to coordinate actions, which stimulates the strengthening of the international knowledge flows. Over time, those institutions interact and contribute to forming a GIS – international institutions cooperating, interacting, and shaping the international nature of innovation, knowledge, etc. It is noteworthy that those institutional developments provide a new basis for the old planetary travels of science and technology.

Those developments do not erase other levels of innovation systems. The emergence of GIS reshapes the different levels of innovation systems: the emergence of layers in those systems reconfigure the hierarchy of innovation systems.

The emergence of GIS either creates new international knowledge flows or intensifies existing ones. This relationship grounds our research strategy to search for evidence of GISs and their emergence in investigating IKFs.

### 1.3. International Knowledge Flows[2]

Once we discussed that GIS has a broader institutional scope, we have to explain why we focused on IKFs and the institutions related to them in our empirical analysis.

Jaffe et al. (2000, p. 215) make a reference that goes back to Griliches (1979): "At least since Zvi Griliches's (1979) seminal paper on measuring the contributions of R&D to economic growth,

[2] This subsection is a revised version of section 1 of a previous text (Ribeiro et al, 2022, pp. 8-10).

economists have been attempting to quantify the extent and impact of knowledge spillovers". Griliches (1992, p. S39), in his turn, writes that "Jaffe (1986, 1988) comes closest in looking for the second type of spillovers, the disembodied kind". These authors are relevant references in a vast literature on knowledge flows that involve different features of this important topic of innovation dynamics, summarized in the following subsections.

At least since Nelson's (1959) and Arrow's (1962) classic papers, which dealt with the properties of basic research and information, including information disclosure in patents, knowledge flows have been discussed in the economics of innovation. Griliches (1979, p. 104) introduces an elaboration on spillovers, stressing that "real knowledge spillovers"... "are the ideas borrowed by research teams of industry i from the research results of industry j" (p. 104). Later, Griliches further elaborates on what we should genuinely consider as knowledge spillovers. According to Hall et al. (2010, p. 1063), Griliches (1992) is a pioneer as he distinguishes two types of spillovers: "rent spillovers and knowledge spillovers".

Knowledge flow presupposes at least two institutions: one generating new knowledge and the other with a very peculiar and challenging capacity to learn – reflecting an absorptive capability (Cohen and Levinthal, 1989, 1990). In other words, knowledge flow presupposes that an institution is at one end of the flow innovating and on another end is another institution either innovating or learning – implementing one of the "two faces" of R&D. Aghion and Jaravel (2015, p. 535), evaluating the contribution of Cohen and Levinthal, discuss the integration between this concept of absorptive capacity and knowledge spillovers in general, as they evaluate "that imitation (or 'technological adaptation') is as much an investment as frontier R&D".

The introduction of absorptive capacity in these flows defines the intensity of spillover: "the more knowledge is codified and higher is the absorptive capacity of other firms, the more knowledge spillover will take place" (Hall et al., 2010, p. 1065).

The absorptive capacity is a crucial concept for our research because it shows that there must be at least two institutions in each knowledge flow, either in knowledge-creating or in knowledge diffusing flows. This approach is vital to explain the unit of analysis of our research, the international knowledge link connecting two institutions.

Jaffe et al. (1993, p. 578) opened a new line of investigation on this subject as they evaluated that "knowledge flows do sometimes leave a paper trail, in the form of citation in patents". These citations contribute to understanding two sets of agents: those who generate knowledge - patent owners (or patent assignees of cited patents) - and those that can learn and use the information of that accumulated stock of knowledge to promote technological innovation, leaving racks of this use in citing patents - the patent assignee of the citing patent. Knowledge flows cross national boundaries: Jaffe et al. (1993) highlighted that Grossman and Helpman (1991) "consider explicitly international knowledge spillovers".[3]

Coe and Helpman (1995) pioneered the topic of "international R&D spillovers". Griliches (1979, 1992) was a relevant reference for them. Although Coe and Helpman (1995) do not include

[3] See Grossman and Helpman (1991, pp. 165-171), section 6.5 on “international knowledge flows”.

Cohen and Levinthal (1989, 1990) in their references, they may have an implicit or indirect dialogue with them as they introduce domestic R&D stock in their analysis, which we may interpret as an aggregate measure of absorptive capacity, a tool for the use of international R&D spillovers. For Coe and Helpman (1995, p. 860), "own R&D enhances a country's benefits from foreign technical advances, and the better a country takes advantage of technological advances in the rest of the world, the more productive it becomes."

Branstetter (1998) presents a review of the literature on international knowledge spillovers. The first paper of Jaffe and collaborators on international flows mentions two previous references on "technological flows" - Teece (1977) and Coe and Helpman (1995) (Jaffe et al., 1999, p. 106). Resuming Griliches distinction, Jaffe et al. (1999, p. 106) stress that "[k]nowledge spillovers are much harder to measure than technology transfer, precisely because they tend to be disembodied". Jaffe et al. (1999) pioneered patent citations to track international knowledge flows.

The connection between the literature on international knowledge spillovers and absorptive capacity is essential, as suggested by Cohen and Levinthal (1989, p. 569, footnote 1): in this pioneering paper, they mention this relationship as the international diffusion of knowledge generated by agricultural research depended upon the existence of institutions to absorb them as Evenson and Kislev (1973) had shown. Aghion and Jaravel (2015) explore other aspects of a potential dialogue among the authors discussing international knowledge (or R&D) spillovers and absorptive capacity. As discussed in subsection 1.4, this dialogue defines the choice of our basic unit of analysis – IKLs connecting institutions as their nodes.

This vast literature on knowledge flows may be summarized by some significant flows described by relevant papers. Table 1 presents six types of knowledge flows, describing their nature, traceability, and related papers. All these flows have been analyzed, including the international dimension – an essential feature for our analysis. Table 1 shows selected international knowledge flows related to knowledge creation or diffusion, including both codified and tacit knowledge and scientific and technological knowledge – all essential knowledge flows for innovation systems.

**TABLE 1**
**Types of Traceable International Knowledge Flows - Nature, how to trace them and related literature**

| Type | Nature | How To Trace It | Discussed By |
|---|---|---|---|
| Scientific citation of scientific papers | INPUT FOR NEW KNOWLEDGE AND/OR DIFFUSION OF KNOWLEDGE | SCIENTIFIC PAPER CITATION OF SCIENTIFIC PAPERS | Bornmann et al (2018), Abramo et al (2018) |
| Collaboration in science | CREATION OF NEW KNOWLEDGE | CO-AUTHORSHIP OF PAPERS | Glänzel and Schubert (2005) |
| Co-invention in patents | CREATION OF NEW KNOWLEDGE | CO-INVENTORS IN A PATENT | Breschi and Lisoni (2004) |
| Forward patent citations of patents | DIFFUSION OF KNOWLEDGE | PATENT CITATION OF PATENTS | Jaffe and Trajtenberg (2002) |
| Backward patent citations of patents | INPUT FOR NEW KNOWLEDGE | PATENT CITATION OF PATENTS | Jaffe and Trajtenberg (2002) |
| Patent citation of scientific papers | INPUT FOR NEW KNOWLEDGE | PATENT CITATION OF SCIENTIFIC PAPERS | Narin et al (1997) |
| Production and innovation activities within an MNC | CREATION WITHIN TNCs | PATENT INVENTOR COUNTRY DIFFERENT FROM PATENT ASSIGNEE | Bathel and Li (2020) |

Source: Authors' elaboration

Patents are a fundamental source for tracking four knowledge flows shown in Table 1 – patent co-inventors, patent citation of patents (both backward and forward citations) and patent citations of scientific papers. Scientific papers leave traces of two knowledge flows – co-authorships and their use as knowledge inputs in patents. The structure of transnational corporations – a proxy of relationships among headquarters and their subsidiaries – reveals tacit knowledge necessary for these corporations' productive and innovative activities.

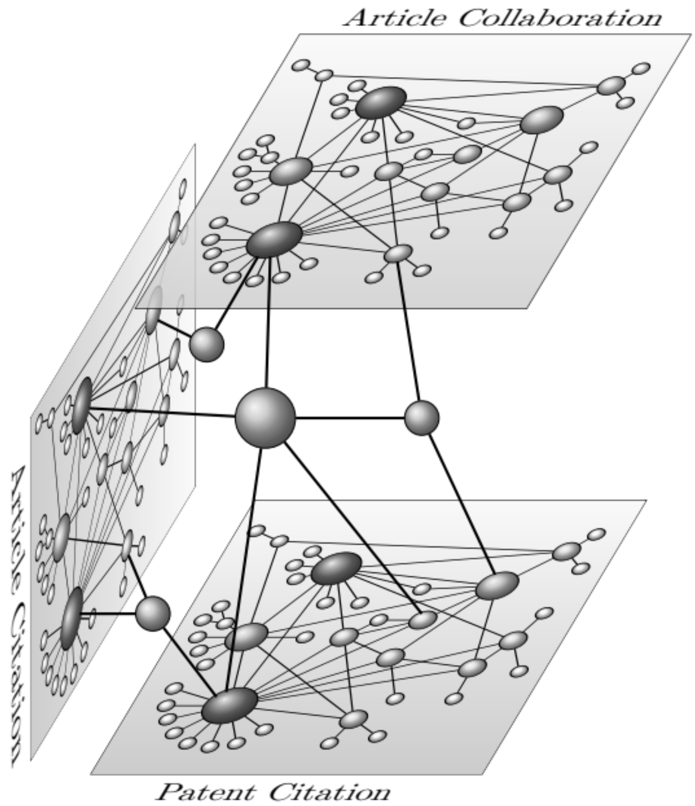
Table 1 also helps to explain why our paper underestimates these international knowledge flows since, as we will show in section 2, we concentrate our investigations on four of these seven international knowledge flows (rows in Table 1). So, it is possible to assume that the complexity of links and flows from which the Global Innovation System emerges is even more intense.

## 2. COMPLEX NETWORKS AND COMPLEX SYSTEMS

We can represent the IKFs and the institutions that create them as a network where the nodes represent the institutions, and the links connecting the nodes represent the IKFs. Each international knowledge link (IKL) - the network representation of the IKF - connects two institutions - nodes - from different countries.

As we empirically analyze three kinds of IKFs, we can organize the entire network as three layers, each containing the links and the respective nodes associated with a specific flow kind, as Figure 1 shows.

**FIGURE 1**
**Network Illustration**




Source: Ribeiro et al (2022, p. 21)

When we solely analyze each layer's network structure, we figure out they are scale-free networks. This kind of network has peculiar properties due to how we built them. We start the growth process with very few nodes fully connected to each other. Then we begin adding new nodes by connecting them to an existing node in the network with a probability proportional to the number of connections the network node already has. So, this preferential attachment concentrates new connections in the nodes that already have more connections and keeps poorly connected nodes with few connections (Barabasi and Domany, 1999). Literature refers to it as Mathews' law.

This odd connection distribution leads to two fundamental properties for our future discussion in the context of the emergence of the GIS: implicit hierarch and robustness. The hierarch occurs because the pretty few nodes that are vastly connected to the rest of the network, hereafter hubs, will dominate these rest nodes' dynamics and, therefore, the significant network part. Then, if we change the state of the hubs, the network state will alter as a whole. The robustness occurs due to if we randomly attack the network by depleting some nodes, the network structure will not significantly change because it is highly likely we only deplete poorly connected nodes. As the most critical nodes - hubs - are pretty few compared to the network size, it is quite unlike for us to pick up them randomly, depleting them, which would have a higher impact on the network dynamics (Albert and Barabasi, 2002).

Barabasi (2017) argues that scale-free networks are associated with self-organized systems because the preferential attachment rule raises spontaneously from an endogenous organization of the system elements and not due to an exogenous agent that calculates the connection number of each node and picks up the node that will receive a new connection. In addition, complex systems present this property of self-organization. So, we can associate scale-free networks with the output of complex systems (Wagner and Leydesdorff, 2005).

We can define complex systems as those formed by vast elements interacting with each other, showing different organizations in different aggregation scales (Goldenfeld and Kadanoff, 1999). Due to their organization, those systems spontaneously present a correlation length similar to the system size. Therefore, each element state correlates to all other system elements. This characteristic leads to a non-linear response when the system is perturbated because a local perturbation will propagate through the systems due to the high correlation length altering the state of a significant part of the system.

Because of that, we suggest that recently IKLs increased at such a level creating a global layer that connects the different NSIs so that changes in a specific NSI propagate through the international links of the global layers to other NSIs, altering their dynamics and impacting the system behavior as a whole. At the same time, the spread of relevant knowledge tends to be strengthened with the gradual consolidation of the networks that conform a Global Innovation System, generating important feedback effects on NISs.

## 3. NETWORK OF NETWORKS AND ITS EVOLUTIVE PATTERNS

As Figure 1 shows, our network representation of the IKFs does not create purely isolated layers but entangled layers connected by institutions that create more than one type of knowledge flow, hereafter multi-layer nodes or multi-skilled institutions.

Multi-layer networks refer to relational systems whose units are connected by different relationships, with links of distinct types embedded in different layers. According to Boccatelli et al. (2014, p. 5), "[m]ulti-layer networks explicitly incorporate multiple channels of connectivity and constitute the natural environment to describe systems interconnected through different categories of connections". For Hammoud and Kramer (2020, p. 2), "the simplest definition of a multi-layer network is a set of nodes, edges, and layers, where the interpretation of the layers depends on the structural characteristics of the model".

The combination and overlapping of networks mediated by nodes that connect different layers may be related to the concept of "multiplex networks" (Kivelä et al., 2014; Domenico et al., 2013). For Wasserman and Faust (1994, p. 422), "multiplexity of relations is the tendency for two or more relations to occur together". This literature defines multiplex networks as a subset of multi-layer networks where we can find a set of nodes that is part of different networks.

It is possible to observe multiplexity in many contexts, from social network analysis to economics, medicine and ecology. Multiplex networks are everywhere, from multimodal transportation systems to multifaceted social relationships and biological interactions taking place through different channels (Hajibagheri et al., 2016). Some of the best well-known network datasets, such as the co-authorship network of scientists, are multiplex networks, with scientific collaborations being distinguished according to the area of research.

The notion of multiplex can be applied to unveil the richness associated with high levels of complexity, focusing on fundamental aspects and providing new tools for analyzing the structure and dynamics of real-world systems. So, there has been a growing interest in examining the temporal dynamics of multiplex networks (Attanasio et al., 2021; Thompson et al., 2017; Battiston, 2017; Cozzo, 2016). In this context, it is essential to consider how agents organize their interactions across layers and how this affects the system's dynamics over time. So, multi-layer networks may also allow for modelling intertwined dynamical processes on interacting layers.

Temporal network theory is an extension of network theory that many authors have applied to model dynamic processes in economics, social sciences and engineering (Thompson et al., 2017). Organizing the dynamic multiplex network as layers composed of a single edge type linking the same underlying vertices can reveal interesting aspects of how cross-layer interaction patterns evolve. In coevolving networks, links in one layer increase the probability of other types of links forming between the same node pair. The massive amount of data available and the various types of interactions, which co-exist and evolve in time, make a description based on the evaluation of temporal and multiplex dimensions necessary.

Temporal networks, whose edges are intrinsically dynamic, allow for uncovering properties of time-varying networks. We can move in this direction by expanding upon the definitions of network theory to cover its dynamic properties.

While some of the measures of the patterns of connectivity are valid for all types of multi-layered networks, time is a particular case since it comprises an ordered set. In fact, when the analysis contains temporal information, the order is crucial. For example, consider a set of three cities, three transportation types and three years. Here, each edge is expressed in a multigraph - formed as a set of nodes and their linkages - connecting two cities by transportation type and year. In such complex multigraphs, the temporal network measures presented can be used to examine relationships across time, allowing to capture their structure and evolution.

## 4. DATA AND METHODOLOGY

### 4.1. The Database and the Knowledge International Flows Identification

Previously the construction of the networks we analyze in this work, we arranged two large and local databases: one covering the metadata of articles indexed on the Web of Science, hereafter ISI, and another covering the metadata of patents granted by the United States Patent and Trademark Office (USPTO), hereafter USPTO.

Regarding the time lapse, we got all articles published in 2009, 2012, 2015 and 2017 and the articles cited by the USPTO patents granted in the same years above, nevertheless the article publication year. For the patents, we got all documents granted by USPTO in 2009, 2012, 2015 and 2017, and those they cited, nevertheless, the cited patent year.

To retrieve the article cited by the patents, once the reference appears as non-structured text, we developed an algorithm to slip the parts of the reference (author, title, journal, and year) and loop up those fields on Web of Science - similarly to Ribeiro et al. (2014).

From these databases, we identify three different types of international knowledge flow as follows:

a) Co-authorship in Science: For each ISI article, we calculated all possible combination pairs among their authors and compared the country of their institutions. We consider an international flow when those countries are different - see Ribeiro et al. (2018).

b) Patent Citation: we compared the first assignee country of the original document to the first assignee country of the cited USPTO patent. We consider an international flow when those countries are different - see Britto et al. (2021a).

c) Article Citation in Patent: we compared the first author institution country of the article to the first assignee patent country. We consider an international flow when those countries are different – see Ribeiro et al. (2014)

### 4.2. Building the Network of Networks

Succeeding the international flows identification, we constructed the network by representing each institution participating in a patent or article with any international flow as its nodes. Then, we connected two nodes when we identified an international flow between them. For example, if Apple (US) co-authored an article with Beijing University (CN), two nodes in the network will represent Apple and Beijing University, and a link will connect them, representing the co-authored article.

As the network nodes represent the institution, a critical step in the network building is the standardization of institutions' names; otherwise, we can identify as different nodes the same institution if it appears with different names in different documents. For example, names such as IBM, International Business Machine Corp, and International Business Machine Corporation that refer to the same company are replaced by a standardized version as just IBM. To implement this standardization, we identified several suffixes related to companies and universities in different languages and removed them from the institutions' names. We also identified the main abbreviations in this context and replaced them with their non-abbreviated version.

After this automatized process, a human checked the results of the most patented and articled institutions, pointing out the potential non-standardized names that we feedback to the algorithm, improving it. We repeated this feedback process until we found pretty few non-standardized names.

Once we have different kinds of international flow, we can organize the network according to the flow type by setting up the nodes that show just one kind of flow and their respective links as layers. So, we constructed three layers related to the article co-authorship, patent citation and article citation in patent flows. Please, see the layers in Figure 1. However, we also have institutions that participate in documents with more than one kind of knowledge flow. In those cases, we locate the node representing the institution out of a specific layer, and, as they have different flows, they will be connected to different layers. Therefore, those nodes will connect two or three layers.

## 5. ANALYSIS: THE STRUCTURE OF IKL

Our analytical framework included a topic on networks because we are dealing with a particular type of network – multiplex networks, a specific form of multi-layer network. We also advanced in an inter-temporal analysis of the evolution of these networks, covering the years 2009, 2012, 2015 and 2017.

As we are dealing with multi-layer networks, there might be nodes that appear in only one of the layers – monolayer nodes – and nodes that more than one layer share – multi-layered nodes. Those multi-layer nodes have a vital role in connecting the different layers. Translating those network characteristics to the innovation systems' language, once an institution participates in more layers, it has better conditions to act either as an absorber of knowledge generated anywhere in those networks or as a creator of knowledge that will spread to other layers.

In our analysis, we also approach the multi-layered nodes from an inter-temporal perspective, reflecting an attempt to advance toward studying the evolutionary network pattern. This analysis shows how a hierarchy within innovation systems might arise and evolve.

### 5.1. Three Layers in an Intertemporal Perspective

The first layer we address temporarily connects co-authors of scientific papers affiliated with institutions in different countries. Table 2 presents data for layer #1 – the network of scientific international collaboration - along the four years covered by our analysis. Since those co-authors and their institutions interact – an active collaboration process in writing a scientific paper – this link is bidirectional. This layer traces collaboration in the generation of new scientific knowledge. The original database of scientific papers was extracted from the Web Of Science, comprising the evolution from 1,885,092 articles in 2009 to 2,774,251 in 2017, as Table 2 details.

**TABLE 2**
**Data on Layer #1:**
**Institutions Connected by IKLs**
**Through International Co-Authorship in Scientific Papers**
**(2009, 2012, 2015 AND 2017)**

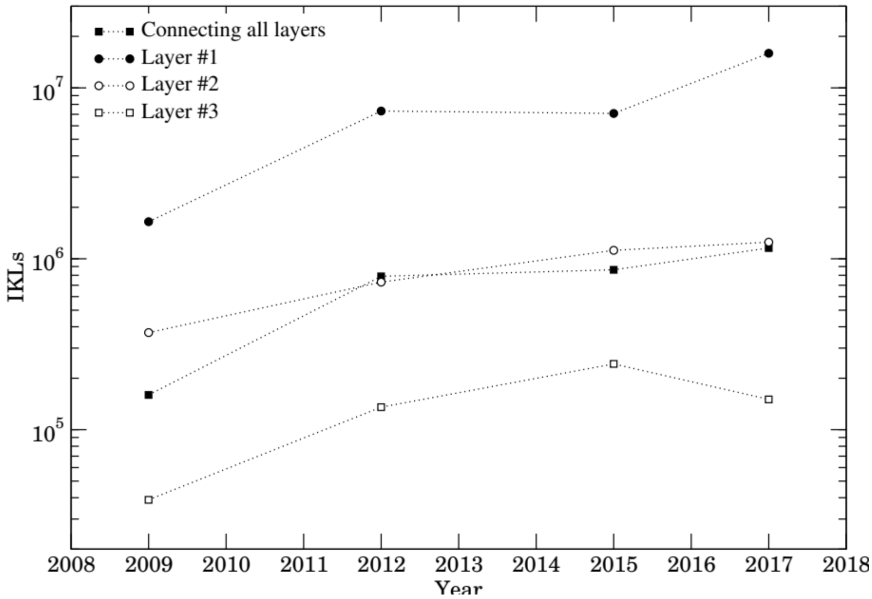
| Year | Articles | Articles with international collaboration | % | Knowledge Links (National and International) | International Knowledge Links | % | Power-Law Exponent |
|---|---|---|---|---|---|---|---|
| 2009 | 1.885.092 | 265.460 | 14,1% | 3.299.230 | 1.646.786 | 49,9% | 1,76 |
| 2012 | 2.019.563 | 329.190 | 16,3% | 10.025.942 | 7.317.107 | 73,0% | 1,74 |
| 2015 | 1.964.747 | 418.866 | 21,3% | 10.315.751 | 7.083.075 | 68,7% | 1,73 |
| 2017 | 2.774.251 | 576.081 | 20,8% | 43.383.852 | 15.920.875 | 36,7% | 1,67 |

Source: WebOfScience, - authors' elaboration

The scientific inter-institutional citations incorporated in these papers evolved from 3,299,230 citations in 2009 to 43,383,852 in 2017 – those totals involve international and domestic knowledge links. During this period, the total scientific papers with international collaboration evolved exponentially from 265,460 in 2009 to 576,081 in 2017, with an annual growth rate of 9.8%. The share of international cooperation in the total amount of scientific papers evolved from 14,1% in 2009 to 20,8% in 2017. From these data, we identified an exponential evolution from 1,646,786 IKLs in 2009 to 15,920,875 in 2017, with an annual growth rate of 28.4%. This evolution is also presented in Graph 1 as the filled circles' curve. The IKLs percentage to the total knowledge flows (domestic or international) evolved from 49,9% in 2009 to 73,0% in 2012, 68,7% in 2015 and 36,7% in 2017.

Beyond the evolution of the number of documents and links of the layer, we also identified this layer network structure by calculating the connection distribution. The curve we obtained as the connection distribution was a power law that characterizes the layer as a free-scale network (Barabasi, 1999). Table 2 also presents this layer's power-law exponent evolution, which falls from 1.76 in 2009 to 1,67 in 2017. This exponent fall means that this layer's implicit hierarchy imposed by the free-scale structure decreased.

**GRAPH 1**
**IKLs EVOLUTION**




Source: WebOfScience, Patstat - authors' elaboration

The second layer comprises international links connecting patent assignees between a citing patent and a cited patent, which we also address temporarily, as illustrated in Table 3.

Since patent assignees cite existing patents – reflecting a process of knowledge absorption and diffusion – an active process occurs only on one side of the knowledge flow; therefore, this link is unidirectional. These links trace two processes: a cited patent shows how knowledge spread (knowledge diffusion), while a citing patent hints at how other assignees use previous knowledge as input for new knowledge. We extracted the patent database from the USPTO data available in XML format. Comprising an evolution from 167,463 patents in 2009 to 319,9831 in 2017. The total of patent citations (international and domestic) in these patents evolved from 3,785,978 citations in 2009 to 11,107,692 in 2017. The total patents with international citation show a seemingly exponential growth followed by a saturation trend, rising from 91,434 in 2009 to 188,980 in 2017. This behaviour differs from the scientific collaboration (layer #1) that showed a free exponential growth. The patent share with an international citation evolved from 54,6% in 2009 to 60,6% in 2015 and fell to 59,1% in 2017. We also identified an evolution from 369,503 IKLs in 2009 to 1,249,320 links in 2017, following a similar behaviour of the patents with an international citation that is a seemingly exponential growth followed by a saturation trend. Figure 3 shows this evolution as the empty circles' curve. The IKLs' share of the total knowledge flows (international and domestic) in this second layer evolved from 9.8% in 2009 to 11.2% in 2017. Table 3 also presents the power-law exponent of the distribution of the connections, implying that this layer also has a free-scale network structure. The exponent fell from 1.83 to 1.75, reflecting that the implicit hierarchy is decreasing.

**TABLE 3**
**Data on Layer #2: Institutions Connected by IKLs**
**Through International Patent Citations of Patents**
**(2009, 2012, 2015 and 2017)**

| Year | Patents | Patents with international patent citation | % | Knowledge Links (National and International) | International Knowledge Links | % | Power-Law Exponent |
|---|---|---|---|---|---|---|---|
| 2009 | 167.463 | 91.434 | 54,6% | 3.785.978 | 369.503 | 9,8% | 1.83 |
| 2012 | 253.633 | 141.843 | 55,9% | 7.237.299 | 729.598 | 10,1% | 1.79 |
| 2015 | 299.382 | 181.521 | 60,6% | 9.722.446 | 1.120.228 | 11,5% | 1.73 |
| 2017 | 319.983 | 188.980 | 59,1% | 11.107.692 | 1.249.320 | 11,2% | 1.75 |

Source: Patstat - authors' elaboration

The third layer connects patent assignees that cite scientific articles, also considered temporarily, as illustrated by Table 4.

Since patent assignees cite existing scientific papers – a process of knowledge absorption and diffusion – an active process occurs only on one side of the knowledge flow; therefore, this link is also unidirectional.

This network traces an institution (the patent assignee) using knowledge created by another – host of the author(s) of the scientific paper - a hint at how the institution uses the scientific knowledge created by another to generate new technology. The total patents with scientific papers citations evolved from 91,434 in 2009 to 188,980 in 2017. Those patent citations of scientific papers formed 38,860 knowledge links (international and domestic) in 2009, achieved a maximum of 242,495 knowledge links in 2015 and fell to 150,352 knowledge links in 2017.

**TABLE 4**
**Data on Layer #3: Institutions Connected by IKLs**
**Through International Patent Citations of Scientific Papers**
**(2009, 2012, 2015 AND 2017)**

| **Year** | **Patents** | **Patents with international article citation** | **%** | **Knowledge Links (National and International)** | **International Knowledge Links** | **%** | **Power-Law Exponent** |
|---|---|---|---|---|---|---|---|
| 2009 | 167.463 | 1.876 | 1,1% | 38.860 | 6.326 | 16,3% | 1,37 |
| 2012 | 253.633 | 10.775 | 4,2% | 135.452 | 59.652 | 44,0% | 1,53 |
| 2015 | 299.382 | 15.252 | 5,1% | 242.495 | 118.571 | 48,9% | 1,51 |
| 2017 | 319.983 | 15.799 | 4,9% | 150.352 | 70.667 | 47,0% | 1,57 |

Source: WebOfScience, Patstat - authors' elaboration.

From our data on patent citations of scientific articles, we identified a monotonical growth of patents with international article citations from 1,876 patents in 2009 to 15,799 in 2017. The number of IKLs in this layer rose from 6,326 in 2009 to 118,571 links in 2015, then fell to 70,667 links in 2017; that is a different behaviour either layer #1 or layer #2 because a fall trend is present in this layer - please, see the empty square curve in Graph 1. The IKLs' share of the total knowledge flows (international and domestic) in this third layer evolved from 16,3% in 2009 to 47,0% in 2017, going through a maximum of 48,9% in 2015. Table 4 also presents the power-law exponent evolution of this layer, i.e. it also has a free-scale network structure, which rose from 1,37 in 2009 to 1,57 in 2017, indicating an increase in the implicit hierarchy imposed by the scale-free that is an oposit behaviour of layers #1 and #2.

It is noteworthy the different behaviour of the three layers' IKLs dynamics we showed in Graph 1. Layer #1 IKLs follow an exponential growth (accelerated growth), layers #2 IKLs show a seemingly saturated trend growth (decelerate growth), and layers #3 IKLs have a decreasing trend in the last year (negative growth). We also identified behaviours in the hierarchy dynamics; layers #1 and #2 decreased their hierarchies while layer #3 increased that.

### 5.2. Two-Layer Nodes in an Inter-Temporal Perspective

This section investigates how those three layers investigated in the previous section connect each other, looking for what they might have in common: nodes that belong to more than one layer. Therefore, we are looking for multi-layered nodes – two-layered nodes in this case.

In this sense, Table 5 displays the total nodes and documents (articles or patents) associated with connecting two different layers, for which we consider all possible combinations between two layers. As a reference, Table 5 also shows the documents of each layer, extracting the information already displayed in Tables 2, 3 and 4. The documents sum of the three layers evolved from 358,770 in 2009 to 780,498 in 2017, and the total number of documents associated with connecting two layers rose from 101,875 links in 2009 to 301,361 links in 2017.

The connections between two different layers comprise several nodes representing institutions that are well-positioned in the global process of knowledge generation, diffusion and absorption, which evolved from 1,359 institutions in 2009 to 5,347 institutions in 2017 (see Table 5)

The institutions shared by layers #1 and #2 are involved in a scientific collaboration to generate new knowledge and are learning with knowledge generated abroad – international patent citation. According to Table 5, institutions in both layers evolved monotonically from 468 in 2009 to 782 in 2017, while the related documents evolved monotonically from 51,383 in 2009 to 125,334 in 2017.

The institutions shared by layers #2 and #3 have a strong learning side, aiming either at the technological dimension – cross-border patent citations – or the scientific dimension – cross-border patent citation of scientific papers. According to Table 5, institutions in both layers evolved monotonically from 760 in 2009 to 4,203 in 2017, while the related documents evolved monotonically from 39,156 in 2009 to 127,406 in 2017.

The institutions shared by layers #1 and #3 combine direct involvement in generating knowledge through cross-border co-authorships and patenting practices, including cross-border citations of scientific papers. According to Table 5, institutions in both layers evolved monotonically from 131 in 2009 to 362 in 2017, while the related documents evolved from 11,336 in 2009 to 48,621 in 2017.

**TABLE 5**
**Data on Documents and Nodes Overlapping Multiple Layers**
**(2009, 2012, 2015 and 2017)**

| LAYER | YEAR | NODES | Layer #1: Articles w/ international co-authorship | Layer #2 Patents w/ international patent citations | Layer #3 Patents w/ international citations of scientific papers | SUM |
|---|---|---|---|---|---|---|
| BASIC LAYERS | 2009 | 155,972 | 265,460 | 91,434 | 1,876 | 358,770 |
| | 2012 | 185,371 | 329,190 | 141,843 | 10,775 | 481,808 |
| | 2015 | 272,960 | 418,866 | 181,521 | 15,252 | 615,639 |
| | 2017 | 308,319 | 576,081 | 188,980 | 15,437 | 780,498 |
| Multi-layer #1-#2 | 2009 | 468 | 25,457 | 25,926 | - | 51,383 |
| | 2012 | 620 | 37,250 | 37,076 | - | 74,326 |
| | 2015 | 748 | 47,853 | 56,667 | - | 104,520 |
| | 2017 | 844 | 67,790 | 57,544 | - | 125,334 |
| Multi-layer #2-#3 | 2009 | 760 | - | 37,503 | 1,653 | 39,156 |
| | 2012 | 2,958 | - | 80,684 | 9,301 | 89,985 |
| | 2015 | 4,008 | - | 112,021 | 14,263 | 126,284 |
| | 2017 | 4,203 | - | 112,539 | 14,867 | 127,406 |
| Multi-layer #1-#3 | 2009 | 131 | 10,807 | - | 529 | 11,336 |
| | 2012 | 296 | 27,070 | - | 2,669 | 29,739 |
| | 2015 | 379 | 31,442 | - | 4,599 | 36,041 |
| | 2017 | 401 | 44,414 | - | 4,207 | 48,621 |
| TOTAL TWO-LAYERED NODES | 2009 | 1,359 | 36,264 | 63,429 | 2,182 | 101,875 |
| | 2012 | 3,874 | 64,320 | 117,760 | 11,970 | 194,050 |
| | 2015 | 5,135 | 79,295 | 168,688 | 18,862 | 266,845 |
| | 2017 | 5,347 | 112,204 | 170,083 | 19,074 | 301,361 |
| THREE-LAYERED NODES | 2009 | 128 | 10,762 | 20,710 | 526 | 31,998 |
| | 2012 | 280 | 26,238 | 34,958 | 2,650 | 63,846 |
| | 2015 | 343 | 29,022 | 50,477 | 4,216 | 83,715 |
| | 2017 | 365 | 41,313 | 50,089 | 3,976 | 95,378 |

Source: WebOfScience, Patstat - authors' elaboration

Table 5 shows how entangled the layers are two by two: in 2009, 28% of the documents with international flows were involved in two-layers connections, while in 2017, 39% of those documents were involved in two-layers connections, going through a maximum of 43% in 2015. Table 5 also displays how concentrated the layers' entanglement is: in 2009, we had 1,359 nodes involved in two-layer connections, corresponding to only 0.87% of total nodes, and in 2017, 1.73% of total nodes were involved in two-layer connections.

## 5.3. Three-Layered Nodes and the Networks Entanglement

Over the four years considered in the inter-temporal analysis, we observed an expressive growth of three-layered nodes: while in 2009, from 1,359 two-layered nodes, it was possible to identify 128 three-layered nodes, in 2017, from 5,347 two-layered nodes, it was possible to identify 365 three-layered nodes (see Table 5). Furthermore, the participation of those three-layered nodes in documents with IKF evolved monotonically from 31,998 in 2009 to 95,378 in 2017.

Those three-layer nodes and their links create a special sub-network that connects all the layers entangling them and turning the three solely layers into a network of networks. In 2009, 128 nodes connected the three layers, and in 2017, 365 nodes connected the three layers.

**TABLE 6**
**Participation of Three-Layered Nodes in IKLs**
**(2009, 2012, 2015 AND 2017)**

| Year | IKLs Layer #1 | IKLs Layer #1 connected to three-layer nodes | % | IKLs Layer #2 | IKLs Layer #2 connected to three-layer nodes | % | IKLs Layer #3 | IKLs Layer #2 connected to three-layer nodes | % | Total IKLs | Total IKLs connected to three-layer nodes | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2009 | 369,503 | 77,934 | 21,1 | 6,326 | 1,636 | 25,9 | 1,646,786 | 80,193 | 4,9 | 2,022,615 | 159,763 | 7,9 |
| 2012 | 729,598 | 165,079 | 22,6 | 59,652 | 10,158 | 17,0 | 7,317,107 | 613,993 | 8,4 | 8,106,357 | 789,230 | 9,7 |
| 2015 | 1,120,228 | 291,129 | 26,0 | 118,571 | 19,362 | 16,3 | 7,083,075 | 550,974 | 7,8 | 8,321,874 | 861,465 | 10,4 |
| 2017 | 1,249,320 | 297,338 | 23,8 | 70,667 | 15,334 | 21,7 | 15,920,875 | 841,886 | 5,3 | 17,240,862 | 1,154,558 | 6,7 |

Source: WebOfScience, Patstat - authors' elaboration.

Considering the total IKLs analyzed and the links connecting the three layers, we can observe a growing process of entanglement, as depicted in Table 6. The IKLs connecting the three layers grew monotonically from 159,763 in 2009 to 1,154,558 in 2017. During these periods, the share of the IKLs connecting three-layer grew from 7.9% in 2009 to 10.4% in 2015 and decreased to 6.7% in 2017. Probably due to the fast growth of the general international collaboration in scientific papers.

This set of three-layer nodes has a pretty peculiar rule turning the three layers into a network of networks, correlating the scientific collaboration, patent citation and article citation in patents, that suggest a role for the organization of the innovation systems as a whole.

### 5.4. Institutions

Institutions are the nodes of our network, the starting and ending point of each IKL. The investigation of the three layers and their overlapping in the previous sub-sections shows how the network of networks grew over time and got more entangled. The number of institutions involved also grew, indicating how international interactions among institutions are becoming more critical for the innovation systems.

Table 7 summarizes the growth of institutions connecting the three layers over time.

**TABLE 7**
**Institutions (nodes) in each layer**
**(2009, 2012, 2015 and 2017)**

| Basic Layer | 2009 | 2012 | 2015 | 2017 |
|---|---|---|---|---|
| Art-Col-Art | 30,178 | 36,156 | 43,789 | 62,186 |
| Pat-Cite-Pat | 18,522 citing<br>104,689 cited | 26,435 citing<br>110,296 cited | 31,742 citing<br>178,374 cited | 34,112 citing<br>197,300 cited |
| Pat-Cite-Art | 817 citing<br>1,766 cited | 3,284 citing<br>9,200 cited | 4,523 citing<br>14,532 cited | 4,699 citing<br>10,022 cited |

Source: WebOfScience, Patstat - authors' elaboration

An investigation of the nature of those institutions is an important topic. For 2017 we found that those layers had different features (Ribeiro et al, 2022, p. 18). The first layer – scientific co-authorship – is a university-led layer (there are 51,194 universities between 62,186 those nodes. The second layer – patent citing patents – is a firm-led network (there are 32,519 firms between those 34,207 nodes). And the third layer - patent citing scientific papers – is another firm-led network (there are 4,193 firms between those 4,721 nodes).

The predominant role of firms in overlapping and entangling the three layers is an empirical regularity. Table 8 shows the crucial role of firms: they are the most common three-layered node, so they are the central connectors turning the three layers into a network of networks. This role is consistent with their crucial position in the innovation systems elaboration.

**TABLE 8**
**Institutions (nodes) in the Networks of Networks**
**(2009, 2012, 2015 and 2017)[4]**

| | 2009 | 2012 | 2015 | 2017 |
|---|---|---|---|---|
| Total | 128 | 280 | 343 | 365 |
| Universities | 23 | 63 | 86 | 86 |
| Hospitals | 0 | 0 | 4 | 2 |

Source: WebOfScience, Patstat - authors' elaboration

We discussed the growth of the three-layered institutions forming the networks of networks in the previous sub-sections. Table 8 summarizes this growth: from 128 in 2009 to 365 in 2017. We investigated two questions regarding changes from 2009 to 2017: 1) how this growth takes place: new institutions joining a core that grows continuously or this growth is turbulent? 2) How does this growth take place regarding those institutions' national origins? This international dimension is becoming more internationalized?

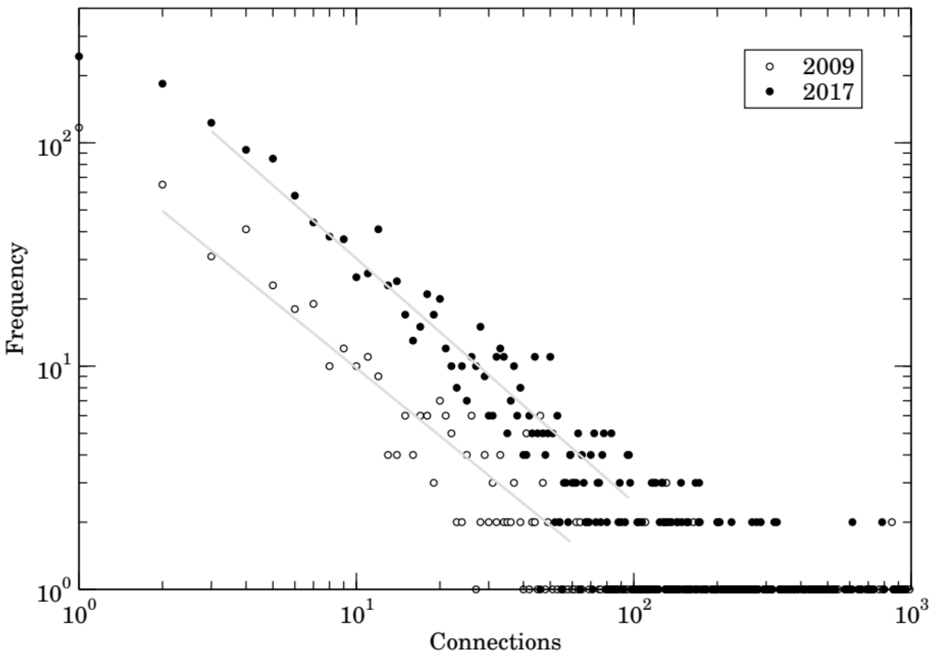
For the first question, the answer is that this growth is turbulent. The growth in the number of three-layered institutions is not just the addition to a persistent core: only 61 institutions in the list of 128 three-layer institutions in 2009 are also present in the other years – less than 50% of institutions. This core has 17 universities (all from the USA), a Korean research institute, and the rest are firms – predominantly from the USA, but also from European countries, Japan, South Korea and Taiwan. It is important to stress that there were no institutions from China in 2009.

For the second question, the growth of institutions includes the participation of new countries in that list – China, India, Australia, Saudi Arabia, Qatar, Israel, Lithuania, United Arab Emirates, and South Africa are countries not listed in 2009 that joined to the three-layered level later.

Finally, we investigated the sub-network structure formed by the three-layered nodes and their connections. Graph 2 displays the distribution of connections in 2009 and 2017 that follow a power-law curve showing that the sub-network connecting the three layers also has a free-scale network structure. Graph 2 shows data only for 2009 and 2017 to ease the visualization, but we analyzed all other years and presented the power-law exponent in Table 9.

[4] The Search in the Excel data was very simple – a search for “univ” returned the data shown in the second line of Table 8 and a search for “hosp” returned the data shown in the third line.

**GRAPH 2**
**Three-layer nodes, number of connections with the three layers and their frequency (2009-2017)**




Source: USPTO, WebOfScience, authors' elaboration.

Those power-law exponents shown in Table 9 are evidence that the sub-network connecting the three layers are not random networks. This finding is important because there is no predetermination that three networks with power-law properties should generate a network with those properties when they overlap, entangle and form a new level in the system.

**TABLE 9**
**Power-law exponents for the networks of networks – the three-layer institutions and their connections to the three layers (2009, 2012, 2015 and 2017)**

| Year | Power-law exponent |
|---|---|
| 2009 | 1.01 |
| 2012 | 1.02 |
| 2015 | 1.06 |
| 2017 | 1.09 |

Source: WebOfScience, Patstat - authors' elaboration

## 6. CONCLUSION

The theoretical background elaborated informed by the innovation systems literature suggest a permanent role for the international dimension in innovation processes. Science and technology have a structural dynamic that cross national borders by multifarious ways. National systems of innovation, once formed using foreign knowledge as important starting points, establish durable international connections that feed their internal dynamics. Over time those connections grow in importance and in institutional forms. Those institutionalization of international relations between NISs introduce changes in those systems, among them the beginning of processes that create new dimensions in innovation systems: an international dimension is added to the existing components of innovation systems – national, regional, sectoral and local. This international new dimension does not replace any previous existing level, only includes a new one, establishing a new hierarchy among those components.

Our research strategy is based on the identification of international knowledge flows connecting institutions in two different national innovation systems: international knowledge links (IKLs). The growth in size and scope of those IKLs is evidence of an international dimension in innovation system – the emergence of GISs.

This paper presented data showing how those IKLs form three basic international layers (collaboration in science, patent citations of patents and patent citations of scientific articles) and how those IKLs organize networks that overlap and entangle. The contribution of this paper is an investigation of the intertemporal behavior of the three basic international layers of innovation systems.

The findings presented in this paper support our conjecture of consolidation of those international layers as evidence of the emergence of a GIS.

The comparison between the size, the structure and the nature of those basic layers show their continuous growth – from 2,022,615 IKLs in 2009 to 17,240,862 in 2017. This growth is a consequence of a systematic expansion in the number of institutions involve in those international knowledge flows – from 155,972 in 2009 to 308,319 in 2017 (see Table 7).

The size and growth of those international layers rearrange the hierarchy with other levels of innovation systems. With the consolidation of those new layers, local and regional located institutions can be domestically connected with institutions that are part of international networks. Small world properties may help isolated local institutions to tap to international knowledge flows using only domestic connections. Opportunities such as those are very important for public policies in current times – and this may be a concrete example of how to use the new hierarchy of innovation systems.

Those basic layers overlap and entangle – a process of self-organization of international knowledge links -, and these overlapping and entanglement have a dynamic that involves a growing number of institutions developing the ability to be connected to more than one layer. The number of two-layer institutions grows from 1,359 in 2009 to 5,347 in 2017. The number of three-layer institutions also grows, from 128 in 2009 to 365 in 2017. Those diverse forms of growth – co-evolutionary forms of growth – describe how those basic layers are becoming both larger and more entangled.

The growth and entanglement of those basic three layers is analyzed in this paper, that uncovers an important structural feature of those networks – they are free-scale networks, therefore, networks that have properties such as hierarchy, small-world and self-organization.

Another important contribution of this paper is the evaluation of the intertemporal behavior of the network of networks – the three-layer nodes that are the core of those networks. Those core institutions total 128 in 2009 and 365 in 2017. Their network also has free-scale properties, an important indication of robustness of their organization at the center of the whole system.

The intertemporal dynamic can be summarized as the basic networks growing in size and participants, their overlapping and entanglement creating networks of networks – asymmetric multiplex networks, with growth that is not linear or continuous, but witnessing anomalous behavior in the form that new institutions join the core of the system and in the capacity of the three-layer institutions to expand their connections hand in hand with the general growth of the networks.

The growth of the basic networks and of their overlapping and entanglement shows the inclusion of new institutions and new countries in all levels of those networks. The institutional composition of the basic layers shows a differentiation: one of basic networks (scientific international collaboration) is a university-led network, the other two are firm-led networks. However, all other networks, formed by intersection and overlapping of those basic networks are firm-led – this suggests the key role of firms as connectors of those different layers, a role coherent with the expected from the theoretical elaboration on innovation systems.

Those empirical findings help our elaboration on GISs. The stability, robustness and structured growth indicate that those international layers are elements that show how consistent the international dimension of innovation systems are in contemporary capitalism – national borders have been systematically overcome by this evolution of innovation systems.

The GISs are more than the parts analyzed in this paper, but the evidence collected here helps to understand how the constitutive institutions are shaping the whole system. The properties of those basic and entangled networks are important for our evaluation of the current stage of formation of GISs. The robustness of those layers and their resulting networks of networks and the preservation of free-scale properties over time support the conjecture of consolidation of those international layers. This consolidation transforms the nature of innovation systems as those international connections are large and strong enough to represent a structural change in the system. As presented in section 1, our evaluation is that we are in stage 3 of a four-stage process of GIS formation – the level of formation of those three layers and the consistence of that process may be empirical evidence for this evaluation.

We found that each layer follows a free-scale network structure associated with a self-organized system and creates an intrinsic hierarchy. The subnetwork that connects the three layers is also a free-scale network. As it is composed of multi-skilled institutions capable of participating in the three types of international flows we analyzed, the hierarchy imposed by this free-scale subnetwork can be understood as a hierarchy inside the hierarchy because the multi-skilled institutions are already configured as special institutions. Therefore, we have a pretty complex network structure that is very unlike being created by a random process.

Furthermore, we identify elements that interact with each other - institutions through international knowledge flows, hierarchy among those elements, association with self-organized systems, robustness, and specialization - when we analyze the predominant sort of institution that composes each layer and the subnetwork that connects the three layers. So, we have the fundamental aspects necessary to define a system. In the context of this analysis, that is the Global Innovation System.

We can also speculate about the functions performed by a GIS still in formation. In this sense, several authors have tested, adopted and further developed an Innovation System function approach, resulting in numerous lists of system functions (Edstand, 2016; Edquist, 2006; Jacobsson and Bergek, 2006) that may be considered. The list of system functions presented by Heekert et al. (2007) is recurrently mention in some studies, being applied to orient empirical analyses, comprising a distinction between seven innovation system functions: 1) Entrepreneurial Activities; 2) Knowledge Development; 3) Knowledge Diffusion; 4) Guidance of the Search; 5) Market Formation; 6) Resource Mobilization; 7) Creation of Legitimacy. In the case of some of the functions mentioned - as in the case of Knowledge Development and Knowledge Diffusion - the role of GIS is more direct, but also to other functions - such as the Guidance of the Search; Resource Mobilization and Creation of Legitimacy - the articulation of international knowledge flows tends also to be relevant.

Finally, the analysis developed here is still exploratory in essence. In order to capture characteristics and evolutionary patterns of GISs, an apparently promising analytical effort comprises the application of complex network analytical tools already used in other fields of knowledge - such as the analysis of multiplex networks in dynamic perspective - to identify important "clues" about the configuration of those systems and their evolution over time.

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