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NETWORKS OF INTERNATIONAL KNOWLEDGE LINKS: NEW LAYERS IN INNOVATION SYSTEMS

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NETWORKS OF INTERNATIONAL KNOWLEDGE LINKS: NEW LAYERS IN INNOVATION SYSTEMS[*]

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SUMÁRIO

ABSTRACT

The unit of analysis of this paper is an international knowledge link (IKL), a knowledge flow that leaves a trace and connects two nodes – different institutions, firms and universities, in different countries. We present and analyze 17,240,834 international knowledge links (data from 2017). These international knowledge links form three basic networks. These three international layers overlap and interweave, forming a network of networks. The contribution of this paper is the identification and preliminary analysis of this overlapping and intertwinement. These networks are robust and their properties suggest a hierarchical structure of a multilayer network that is asymmetric. These networks are interpreted as new layers of innovation systems, with implications for the dynamic of innovation – a reorganization of different levels of innovation systems, now a more complicated structure with interaction between local, sectoral and national levels, as well as these overlapping international networks.

Key-words: International Knowledge flows; Innovation Systems; Networks of networks

JEL classification: O32, O34, O39

RESUMO

A unidade de análise deste artigo é um link internacional de conhecimento (LIC), um fluxo de conhecimento que deixa um rastro e conecta dois nós – diferentes instituições, empresas e universidades, em diferentes países. Apresentamos e analisamos 17.240.834 links internacionais de conhecimento (dados de 2017). Esses links internacionais de conhecimento formam três redes básicas. Essas três camadas internacionais se sobrepõem e se entrelaçam, formando uma rede de redes. A contribuição deste artigo é a identificação e análise preliminar dessa sobreposição e entrelaçamento. Essas redes são robustas e suas propriedades sugerem uma estrutura hierárquica de uma rede multicamada que é assimétrica. Essas redes são interpretadas como novas camadas de sistemas de inovação, com implicações para a dinâmica da inovação – uma reorganização de diferentes níveis de sistemas de inovação, agora uma estrutura mais complicada com interação entre os níveis local, setorial e nacional, bem como com essas redes internacionais sobrepostas.

Palavras-chave: fluxos internacionais de conhecimento: sistemas de inovação, rede das redes

Classificação JEL: O32, O34, O39

INTRODUCTION

This paper presents and analyzes 17,240,834 international knowledge links (data from 2017) that form new layers of innovation systems.

These international knowledge links are traces of international knowledge flows that, as Soete et al (2010, p. 1176) highlight, have shown a "rapid growth" and are a "real challenge for systems of innovation policies, developed primarily within a national context".

The investigation of this "globalization of knowledge flows" (Soete et al, 2010, p. 1176) can start with the huge volume of pertinent literature available. Knowledge flows are important components of innovative dynamic, as Dosi and Nelson (2010, p. 55) put forward: "the 'physiology' of modern capitalism rests on multiple technologies and industries coupled with each other via input-output and knowledge flows". Innovation systems may be seen as institutional arrangements dependent upon a diversity of knowledge flows, connecting firms, universities and research institutions – therefore an important issue of the research agenda on innovation systems is how to trace and measure those knowledge flows (Patel, 1998; Meyer, 2002).

Knowledge flows involve sending and receiving agents. International knowledge links are international knowledge flows that can be tracked, traced and investigated: they are cross-border knowledge flows between different institutions located in different countries. International knowledge links are the unit of analysis adopted in this paper.

The growth of those international knowledge links has been so vigorous that these 17,240,834 international links may be disaggregated into three basic networks. First, 15,920,875 international links connecting authors of scientific papers - a university-led network. Second, 1,249,320 international links connecting inventors of patents that cite foreign patents - a firm-led network. And third, 70,639 international links connecting inventors of patents that cite foreign papers - a second firm-led network. These three international layers overlap and interweave, forming an international network of networks. The contribution of this paper is the identification and preliminary analysis of this overlapping and intertwinement, using as a starting point the characterization of similar networks outlined in existing literature (see section I).

Considering the integrated structure of the three basic networks – international networks – we can refer to the institutions that belong to them as multilayer nodes. They overlap and are intersections of these different networks, performing a special role in defining a hierarchical structure for these networks, whose complex structures and hierarchies are features of complex systems (Anderson, 1972; Goldenfeld and Kadanof, 1999).

The operation of these international layers of knowledge flows may be illustrated by the response of humankind to the global challenge generated by the Covid-19 pandemic. Reports from *The New York Times* describe how researchers located a Harvard University, USA, who were interacting with people from Janssen Pharmac., Belgium, got the news of a sequencing of the virus genome prepared and publicized by scientists from the Fundan University, China (Zimmer, 2020). These reports from *The New York Times* also show these news changed the priorities of scientists working in Biontech, Germany (Gelles, 2020), and Moderna, USA (Lafraniere et al, 2020), focusing them on vaccines for Covid-19.

Is there any relationship between these news related to Covid-19 vaccines and the three international layers presented in our research? Yes, because all institutions mentioned in the previous paragraph (Biontech, Moderna, Janssen, Harvard University and Fundan University) are multilayer nodes integrated in that interwoven network formed by 348 institutions. In other words, the initial steps of humankind in creating a vaccine for Covid-19 were nested in an international network of networks of knowledge flows.

This paper presents, describes and analyzes these three international networks as evidence of new layers of innovation systems. It is organized in six sections. The first section presents the theoretical background. The second section presents data and methodology – a methodology that organizes three steps in our analysis. The third section, outlines the first step of our data analysis – a description of these 17,240,834 international links forming three different layers/networks, with an evaluation of their basic properties. The fourth section addresses the second step of our data analysis – finding multilayer nodes and investigating how they overlap across these three layers/networks. The fifth section presents the third step of our data analysis, focusing on the three-layer nodes - the 348 multilayer nodes that form the network of networks. The final section concludes this paper discussing the implications of these three networks and their interrelationship for the analysis of innovation systems.

I- THEORETICAL BACKGROUND: FROM KNOWLEDGE FLOWS TO NETWORKS OF INTERNATIONAL KNOWLEDGE LINKS

To understand the emergence of new layers of innovation systems, this paper investigates how the literature deals with the issue of knowledge flows, as an introduction to an investigation of international knowledge links and the transformation of innovation systems

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

I.1. Knowledge Flows

Knowledge flows have been discussed in economics of innovation 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. Griliches (1979, p. 104) introduces 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 should be truly considered 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 presuppose at least two actors/institutions: one generating new knowledge and the other with a very peculiar and difficult capacity to learn – reflecting an absorptive capability (Cohen and Levinthal, 1989, 1990). In other words, knowledge flows presuppose that institutions/firms are on one side of the flow innovating and on the other side of the flow 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 an 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 an important concept for our research because it shows how in each knowledge flow there must be at least two institutions, both in in knowledge creating or in knowledge diffusing flows. This approach is important to explain the unit of analysis of our research – an international knowledge link – as connecting two institutions – firms and/or universities (or research institutes or hospitals).

Jaffe et al (1993, p. 578) opened a new line of investigation of this subject as they evaluated that "knowledge flows do sometime 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 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.

I.2. International Knowledge Flows

Knowledge flows cross national boundaries: Jaffe et al (1993) highlighted that Grossman and Helpman (1991) "consider explicitly international knowledge spillovers".[1]

Coe and Helpman (1995) pioneered the topic of "international R&D spillovers". Griliches (1979, 1992) was an important reference for them. Although Coe and Helpman (1995) do not include 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 may be interpreted as an aggregate measure of absorptive capacity, a tool for 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 on 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

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

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) pioneer the use of patent citations to track international knowledge flows.

The connection between literature on international knowledge spillovers and absorptive capacity is important, as suggested by Cohen and Levinthal (1989, p. 569, footnote 1): in this pioneering paper they mention this relationship, as 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 will be discussed in subsection I.4 this dialogue defines the choice of our basic unit of analysis – international knowledge links connecting two institutions as their nodes.

I.3. A Typology of International Knowledge Flows

This huge literature on knowledge flows may be summarized by some important flows as described by important papers.

Table 1 presents six types of knowledge flows, describing their nature, their traceability and related papers. All these flows have been analyzed including the international dimension – a feature that will be essential for our analysis.

Table 1 shows selected international knowledge flows related both to knowledge creation and knowledge diffusion, including both codified and tacit knowledge as well as scientific and technological knowledge – all essential knowledge flows for innovation systems.

Patents are a basic source for tracking four of these knowledge flows – 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 multinational corporations – proxy of relationships among headquarters and their subsidiaries – reveal tacit knowledge necessary for the productive and innovative activities of these corporations.

TABLE 1
Types of International Knowledge Flows, their 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 and Hamilton (1997)
Production and innovation activities within an MNC	CREATION AND/OR DIFFUSION OF KNOWLEDGE	STRUCTURE OF TNCs – connections between headquarters and subsidiaries	Teece (1977), Branstetter (2006)

Source: Authors' elaboration

Table 1 also suggest that our paper may have one problem related to underestimation of these international knowledge flows, since as will be shown in section II we concentrate our investigations on only four of these seven international knowledge flows (lines in Table 1).

These international knowledge flows are the background for our unit of analysis: international knowledge links.

I.4. International Knowledge Links, Layers and Networks

This literature review explains the unit of analysis of our investigation: international knowledge links - knowledge flows that leave a trace, or a knowledge flow that leaves evidence. These international knowledge links connect two institutions from different countries.

These links and the institutions are components of networks – conforming the links and nodes of the pertinent networks. International knowledge links have been investigated in the literature related to networks. The definition of knowledge flows as links, which form networks, has examples in the literature. For patent citation, Erdi et al (2013, p. 227) defined that in their study, "...the patent citation network is comprised of patents (nodes) and the citations between them (links)". For international scientific co-authorship, Wagner et al (2005) investigated links between countries.

The dialogue with Cohen and Levinthal (1989) suggests the definition of institutions as nodes of our international knowledge links – for them firms are the relevant institutions. Theoretically, these links have at one end one institution creating new knowledge and at another end one institution able to use that knowledge and to learn from it – therefore reflecting Cohen and Levinthal's "two faces of R&D": innovation and learning. In their classic paper, the institutions involved in these knowledge flows are firms, more specifically, firms in the innovation system of the United States.[2] However, Cohen and Levinthal (1989, p. 569; 1990, p. 128) speculate on the implications of their elaboration for international knowledge diffusion, with their reference to Evenson and Kisley (1973).

Knowledge flows are active processes, dependent upon efforts to collaborate, to learn and/or to absorb new knowledge. What institutions? Institutions that are components of innovation systems – firms, universities and/or research institutions – incorporating the role of patent assignees and/or workplaces of scientists publishing papers.

Furthermore, the conceptualization of institutions as nodes in the investigation opens room for research on the relationship among different networks that this paper investigates. One node – institution – may be part of more than one network – and this will lead us to investigate nodes that are present in different layers as multilayer nodes.

These international knowledge links and their nodes are components of networks that evolve and self-organize (Érdi et al, 2013; Wagner et al, 2005). The growth of these networks of international knowledge links seems to be a process of formation of new layers in innovation systems: layers that can be analyzed as networks and that in this process may even intertwine, overlap and form networks of networks in this process.

I.5. Multilayer Networks and Network of Networks

Wagner et al (2005) and Strandburg et al (2009) deal with networks and Barabási is a reference for their works. In our review of the literature on networks, Boccaletti et al (2014) and Newman (2010) mention Barabási as related to "monolayer networks".

"Monolayer networks", beyond regular and random networks, deal with growing networks, models that include the mechanism of preferential attachment introduced by Barabási (2016), a mechanism important to explain the emergence of power-law distributions.

These monolayer networks, as investigated by Wagner et al (2005) and Strandburg et al (2009), are important starting points. But the literature has moved on to more realistic and complicated structures, evolving to the characterization of "multilayer networks" (Kivelä et al, 2014).

According to Boccaletti et al (2014, p. 5), "[m]ultilayer 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 multilayer network is a set of nodes, edges, and layers, where the interpretation of the layers depends on the structural characteristics of the model".

[2] For the importance of the Yale Survey for their elaboration, see Cohen and Levinthal (1989, pp. 578-579).

There is a profusion of models of multilayer networks - see, for example, Table 1 in Kivelä et al (2014, pp. 206-207). 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, pp. 218-220; 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". In sum: multiplex networks are a subset of multilayer networks, more specifically, a subset of multilayer networks where we can find a set of nodes that is part of different networks.

These multiplex networks present a feature that is identified in the literature as "correlated multiplexity". According to Lee et al (2014), "[i]n real world complex systems, however, nonrandom structure in network multiplexity can be prominent. For example, a person with many links in the friendship layer is likely to also have many links in another social network layer, being a friendly person. We termed the correlated multiplexity to refer such a nonrandom pattern of network multiplexity. Examples of correlated multiplexity are widespread" (2014, pp. 54-55).

Investigating this correlated multiplexity, the literature finds the most frequent pattern: positively correlated multiplexity. Lee et al (2014, p. 55) explain that this pattern of correlated multiplexity means "that a node with large degree in one layer likely has more links in the other layer as well".

This short review of the literature on networks help us to investigate very basic features of the resulting interrelationship of the layers that these IKLs form.

II. DATA AND METHODOLOGY

II.1. The Database – From Patents And Papers To IKLS

A procedure developed to quantify the international knowledge flows described in the previous section begins with the arrangement of two large and local databases: one covering the metadata of articles indexed on Web of Science, which will be called ISI from here on, and another covering the metadata of patents granted by the United States Patent and Trademark Office (USPTO), which will be called USPTO from here on.

Regarding the group of documents (articles or patents) that fill these databases, each one can be split into two parts according to the date of the document and the reason to get its metadata: the ISI database contains all articles published in 2017, and also the article cited by the patents granted by the USPTO in 2017; the USPTO database contains all patents granted by UPTO in 2017 and the USPTO patents cited by them.

From these starting points – data for 2017 – we extended our databases to include patents and articles cited in the 2017 USPTO patents: therefore, citation of patents or articles by other patents were considered to arrange our local databases. Retrieving the metadata of the cited patents is a simpler procedure because it just needed to loop up the cited patent number on the USPTO search. However, for article citation in the patents, the procedure is far complicated, because the reference to the article appears as non-structured text in the patent. To handle that, an algorithm was developed to include the parts of the reference (author, title, journal, and year) and loop up these fields on Web of Science - similarly to Ribeiro et al. (2014). When the article is found, its metadata are downloaded and added up to the ISI database - this procedure prepared a second part of our database on scientific papers.

One key and strategic stage of the process of construction of our databases is the standardization of the names of the institutions that host the authors of the articles and that are patent assignees. This is not a simple process, because the same institution may have different names in these different sources. This automated process of removal of part of the institution names was implemented to minimize these differences. For example, names such as Google Corporation and Google Corp. were processed to become just Google, increasing the possibilities of a correct matching between our two databases.[3]

From these databases, each of the different types of knowledge flows is identified as follows:

a) Co-authorship in Science: For each 2017 ISI article all possible combination pairs among their authors are calculated and the country of their institution compared - see Ribeiro et al (2018). An international flow is obtained when these countries are different. In 2017 there were 2,774,251 articles and 576,081 with international collaboration.

b) Patent Citation: The citations to other patents of each 2017-granted USPTO patent are identified and then compared the country of the assignee of the cited patent and the original one – see Britto et al (2021). An international flow is obtained when these countries are different. In 2017 there were 352,566 patents and 188,980 with international citations.

c) Article Citation in Patent: The citations to ISI index articles of each 2017-granted USPTO patent are identified as presented above and compared the institution country of the first author of the article and the country of the patent assignee – see Ribeiro et al (2014). An international flow was obtained when these countries are different. In 2017 there were 22,571 patents that cite scientific papers and 15,437 with international citations.

II.2. From IKLs to Networks

Each of these types of international knowledge flows constitute a network of international knowledge links, which organize our investigation and the next section.

Once we have identified all of the international knowledge flows, we may see that they form networks that are traced here and identified as an IKL: two nodes and a flow constituting them shape an international knowledge link (IKL), the basic unit of our analysis. Finally, each of these networks becomes a layer of the entire network because nodes (institutions) that appear in one network may also appear in another one. So, multilayer nodes - the focus of our investigation - may thus be identified.

[3] These matching problems are not trivial. At this point of our research, this stage of the process of matching the different databases is very embryonic, certainly leaving room for much improvement. We are still learning how to organize and improve at this stage. Those comments have an important implication for next sections: our results tend to underestimate the real size of the overlapping networks.

II.3. Methodology: A Three-Step Analysis from IKLS to a Network of Networks

In sum: two nodes and a flow constitute IKLs, IKLs and nodes form networks. These networks organize layers. Therefore, we are dealing with multilayer networks. The investigation of these three layers of IKLs' networks and how they overlap represent the focus of the rest of this paper. We will proceed in three steps, each of them dealing with a different level of aggregation and interaction among these networks. The first step will investigate each layer – each specific international knowledge flow forms a specific international knowledge link -, describing each and looking for their basic properties. The second step starts from the nodes of each of these three layers searching for the nodes that are in more than one layer – multilayer nodes. The third step focuses on the core of these networks – the network of networks -, which is formed by three-layer nodes.

III. FIRST STEP: IDENTIFICATION OF INTERNATIONAL KNOWLEDGE LINKS AND THEIR LAYERS

The unit of analysis in this paper is the international knowledge link (IKL). As presented in section I, an IKF is an international knowledge flow which has left a trace. Therefore, IKLs are a subset of IKFs – an indication that our analysis may be underestimating the real dimension of knowledge flows.

An IKL connects two institutions – two nodes, located in different countries. Institutions are composed of individuals – science and technology personnel, scientists and researchers – that populate firms and universities/research institutions. We are stressing the participation of individuals within these institutions, because they are the authors and inventors of the articles and patents, and as individuals they may have significant interaction through different channels – formally and informally, within their institutions, in conferences, meetings and collaborative research.[4] These personal, work and academic-related interactions seem to go beyond the interactions that leave traces in patent citations and scientific co-authorships – captured in IKLs of this investigation.

In this section we analyze our data presenting features of the IKLs – size, links, and nodes.

III.1. International Knowledge Links Forming Three Layers

Each IKL connect at least two institutions (mainly firms or universities/research institutes). Both institutions are active in these links, as knowledge creators and/or absorbers.

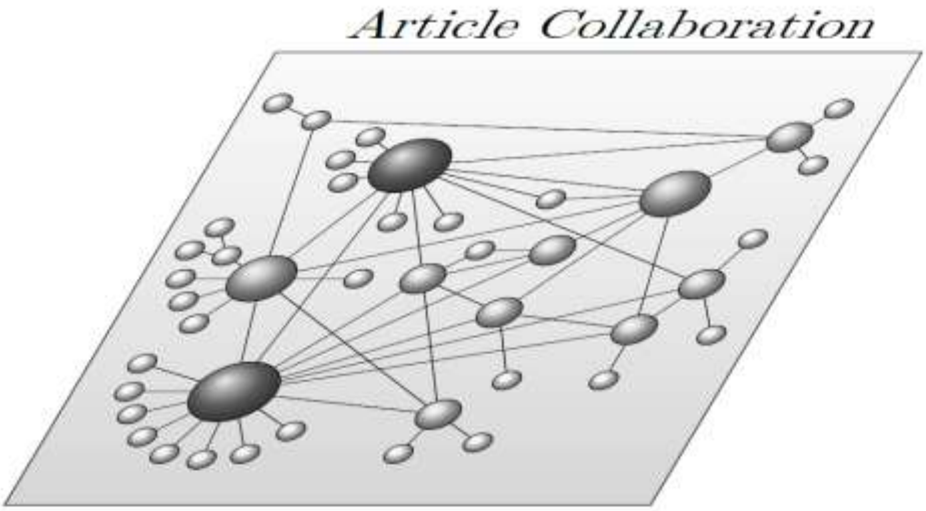
As mentioned above, there are three different types of IKLs investigated in this paper.

The first type of IKL (Figure 1) connects co-authors of scientific papers located in institutions of different countries (see Table 1, second line). Since these co-authors and their institutions interact – an active process of collaborative writing of a scientific paper – this link is bidirectional. This IKL traces collaboration in the generation of new knowledge. From data of scientific papers (WebOfScience, for

[4] See Cohen et al (2002, p. 15) for the importance of these formal and informal channels of interaction.

2017) we identified 15,920,875 cross-border links.[5] These links connect 62,186 nodes – institutions that host the authors of these scientific articles. The predominant institutions in these IKLs are university/research institutions. There are 51,194 universities/research institutes represented in these 62,186 nodes. On the one hand, these data define this set of IKLs as university-led – the five leading institutions are the Chinese Academy of Sciences, University of Oxford, University of Cambridge, Zhezhiang University and UCL. On the other hand, these data show how firms are involved in the process of scientific collaboration, as there are more than 10,000 firms as nodes of these IKLs. The first firm in this ranking is IBM, in the 478th position.

FIGURE 1:
First Layer: A University-Led International Network Of Scientific Collaboration: 62,186 nodes (institutions) and 15,920,875 links (international co-authorships) (2017)



Source: WebOfScience, authors' elaboration

The second type of IKL (Figure 2) connects patent assignees between a citing patent and a cited patent (see Table 1, fourth and fifth lines).

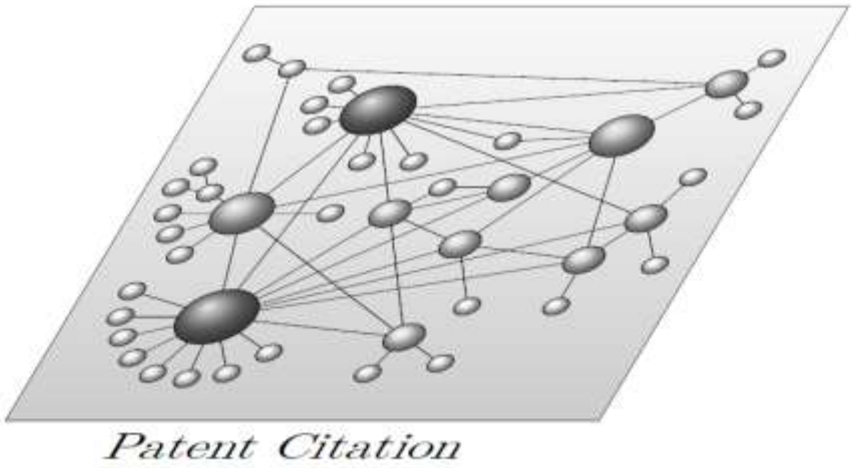
Since the patent inventors cite existing patents – reflecting a process of knowledge absorption and diffusion –an active process occurs only in one side of the knowledge flow, therefore this link is unidirectional. This IKL traces two processes, depending on the point of view of the analyst: a cited patent shows how knowledge is spread (knowledge diffusion) while a citing patent hints how knowledge is used as an input for new knowledge. From our data on patent citations (PatStat, data for 2017), we identified 1,249,320 cross-border links.[6] These links connect 34,207 citing nodes and 197,299 cited nodes – institutions that are patent assignees, employing inventors that are authors of these patents. The

[5] These data confirm the exponential growth of the IKLs, that in 2000 were 545,372 and in 2012 were 7,312,107 (see Ribeiro et al, 2018, p. 167).

[6] These data confirm the growth of these IKLs over time, as Britto et al (2021, p. 718) found 210,271 IKLs in 1991 and 995,296 in 2009.

predominant institution, both among citing and cited nodes are firms. According to our data, among these 34,207 citing nodes there are 32,519 firms, and among these 197,299 cited nodes there are 185,374 firms. Therefore, these data define this set of IKLs as firm-led – the five leading firms are IBM, Samsung, Qualcom, Apple and Microsoft. Although firm-led, our data show that universities are important here – the first university as a citing node in this ranking is MIT, in the 131st position.

FIGURE 2:
Second Layer: A Firm-Led International Network
34,207 citing nodes (institutions), 197,299 cited nodes (institutions)
and 1,249,320 links (cross-border patent citations)
(2017)

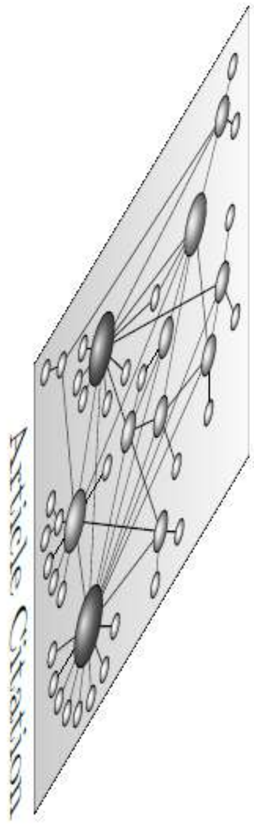


Source: PatStat, authors' elaboration

The third type of IKL (Figure 3) connects patent assignees that cite scientific articles (see Table 1, sixth line). Since the patent inventors cite existing scientific papers – again, a process of knowledge absorption and diffusion – an active process also occurs only on one side of the knowledge flow, therefore this link is unidirectional. This IKL traces one institution (the patent assignee) using knowledge created in other institution – host of the author(s) of the scientific paper, a hint of how one institution uses knowledge created in another to generate new technology. From our data on patent citations of scientific articles (PatStat and WebOfScience, data for 2017), we identified 70,639 cross-border links.[7] These links connect 4,721 citing nodes (patent assignees) with 8,938 cited nodes (institutions with scientific articles) – patent inventors that cite scientific authors in their process of new technology creation. In this type of IKL, there are different predominant institutions, depending on the point of view of the investigation: among the citing nodes firms predominate – 4,193 firms among 4,721 nodes (patent assignees) -, among the cited nodes universities predominate – 4,578 universities among 8,938 nodes. It is important to stress the high share of firms among the cited scientific articles.

[7] We cannot make a direct comparison with our previous investigation on this type of IKF (Ribeiro et al, 2014). However, an indirect hint about the growth of this dimension may be grasped from a comparison between the total of patents which we analyzed with data for 2009 – 10,985 USPTO patents with citations to ISI-indexed papers (note, all patents, with only domestic citations of scientific papers and also patents with cross-border citation of scientific papers) – and our data for 2017 – there are 15,437 USPTO patents with only cross-border citation of scientific papers. Even if all patents in 2009 had only cross-border citations of scientific papers, the growth would have been significant.

FIGURE 3
Third Layer: an International Network Connecting Patents and Scientific Papers
4,721 citing nodes (institutions), 8,938 cited nodes (institutions)
and 70,639 links (cross-border patent citations of scientific papers)
(2017)



Source: USPTO and WebOfScience, authors' elaboration

III.2. Three Networks and Hints of Self-Organization

These three different types of IKLs form different networks' layers. Table 2 summarizes the main features of each layer, with their predominant institution, including the basic data presented in subsection III.1.

Table 2 organizes the data by layers, presenting these data for layer #1 – the network of scientific collaboration displayed by the 15,920,875 IKLs -, layer #2 – the network of patent citations with its 1,249,320 IKLs -, and layer #3 – the network of patent citations of scientific papers with its 70,639 IKLs.

Table 2 introduces an analysis of the structural properties of those networks, as it includes data on the robustness of these networks,[8] investigated through their power-law exponents.

[8] One of the properties of self-organized systems is robustness. A system is robust when it survives shocks – endogenous or exogenous – and combines its survival with changes. Robustness is different from resilience, because resilience means a system that survive shocks preserving its previous shape.

TABLE 2
Basic Data on Each Layer:
Layer, number of links, number of institutions (nodes), links per node, power-law exponent and predominant institution
(2017)

LAYER	LINKS	NODES	LINKS PER NODE	PL EXP	PREDOMINANT INSTITUTION
#1: ART-COL-ART	15,920,875	62,186	256	1.72	University (*)
#2: PAT-CITE-PAT	1,249,320	34,207 citing 197,299 cited	37	2.18	Firm - citing nodes (**) Firm - cited nodes
#3: PAT-CITE-ART	70,639	4,721 citing 8,938 cited	15	1.99	Firm - citing nodes (***) Universities - cited nodes

Source: WebOfScience, Patstat - authors' elaboration
OBS: (*) There are 51,194 universities between 62,186 nodes
(**) Citing nodes: 32,519 firms betwen the 34,207 nodes; Cited nodes: 185,374 firms between the 197,299 nodes
(***) Citing nodes: 4,193 firms between 4,721 nodes; Cited nodes: 4,578 universities between the 8,938 nodes

The power-law exponents of these three networks are 1.72, 2.18 and 1.99 – these figures mean that all three networks are self-organized (Barabási, 2016). This feature of the data for 2017 is compatible with our findings in previous investigations for layer #1 (Ribeiro et al, 2018) and layer #2 (Britto et al, 2021), which showed that these power-law properties persisted over time.

These properties of our three networks indicate an important methodological issue: we are not dealing with simple connections between national innovation systems, but with international self-organized networks that are developing new layers in innovation systems.

International knowledge links organize layers – networks. These networks are self-organized structures. Once we have described these three networks, the second step of our analysis is to investigate how they overlap and interact. What is the outcome of the overlapping of these three self-organized networks?

IV. SECOND STEP: MULTILAYER NODES

IV.1. Description of Two-Layer Nodes

Our literature review included a topic on networks because our conjecture is that we are dealing with a very specific type of network – multiplex networks, a specific form of multilayered networks.

This section tries to investigate how these three basic networks described in section III interact. It also begins looking for what they might have in common: nodes that are part of more than one layer. Therefore, we will examine essentially multilayered nodes.

There are 307,351 nodes in the 17,240,834 IKLs identified in our investigation. As self-organized networks, displaying the power-law exponents shown in Table 2, these structures show strong hierarchical properties, which present an uneven distribution of IKLs by nodes. The properties of these networks displayed by the power-law structure suggest the existence of hubs – nodes that concentrate many IKLs. In the case of our three networks, some of these hubs may also be differentiated through their presence in more than one network.

This conjecture suggests that we need to think about a new feature derived from the interaction between these three networks: there might be nodes that exist in only one of these networks – monolayer nodes – and nodes that might be found in more than one network – multilayer nodes. These multilayer nodes (or hubs) may have a very important role as connectors of these different networks. Translating these properties of networks into the language of innovation systems, as an institution participates in more layers it has better conditions to act either as an absorber of knowledge generated elsewhere in these networks or as a creator of knowledge that will spread to other layers. This analysis shows how a hierarchy within innovation systems may be organized.

A starting point in this analysis is shown in Table 3, that summarizes the total of nodes that are in the overlapping of two different networks.

Table 3 shows the hierarchical structure of the interconnections of these three networks: from 307,351 nodes in these three international layers (Table 2), we find 5,347 nodes that are found in at least two networks (Table 3).

TABLE 3
Data on Basic Networks
(Each Line is an Intersection Between Two Layers Of Table 2)
(2017)

Basic Networks	Nodes	Universities
#1#2	782	170
#2#3	4,203	376
#1#3	362	83

Source: WebOfScience, Patstat - authors' elaboration

IV.2. What Does it Mean to be in at Least Two Networks?

These 5,347 two-layer nodes represent institutions that are well-positioned in the global process of knowledge generation, diffusion and absorption.

The 782 institutions that are both in the first and second layers are institutions that are involved in the process of scientific collaboration to generate new knowledge – cross-border co-authorships – and are learning with knowledge generated abroad – cross-border patent citation. According to Table 3, 170 universities are in these two layers (21.7% of these nodes). The rankings of these two-layer nodes are asymmetric, as the first firm in the ranking of layer#1 is IBM in position 72 and the first university in layer #2 is Tsinghua University in position 75. After the position 678 there are only institutions with one cross-border co-authorship and one cross-border patent citation. These 782 institutions represent 10.1% of all scientific papers with cross-border co-authorships and 27.3% of all patents with cross-border patent citations.

The 4,203 institutions that are in the second and third layers have a strong learning side, aimed both at the technological side – cross-border patent citations – and at the scientific side – cross-border patent citation of scientific papers. Since both layers #2 and #3 are firm-led – universities are only 8.9% of the set of two-layer nodes described in Table 3 -, this is the less asymmetric of our sets of two-layer nodes, as there are six firms that are both in the rankings of layer #2 and layer #3. After the position 2,953 there are only institutions with one cross-border patent citation and one cross-border patent citation of scientific papers, these 4,203 institutions have 59.5% of all patents with cross-border patent citations and 96.2% of all patents with cross-border citation of scientific papers.

The 362 institutions that are in the first and third layers combine direct involvement in the generation of knowledge through cross-border co-authorships and patenting practices that include cross-border citations of scientific papers. This overlapping of networks is also very asymmetrical, as one is firm-led and the other is university-led. The first firm in the ranking of layer #1 is IBM in the position 44 and the first university in the ranking of layer #3 is Northeastern University in the position 19. After the position 398 there are only institutions with one cross-border co-authorship and one cross-border patent citation of scientific papers, these 362 institutions represent 6.0% of all scientific papers with cross-border co-authorships and 23.7% of all patents with cross-border citation of scientific papers.

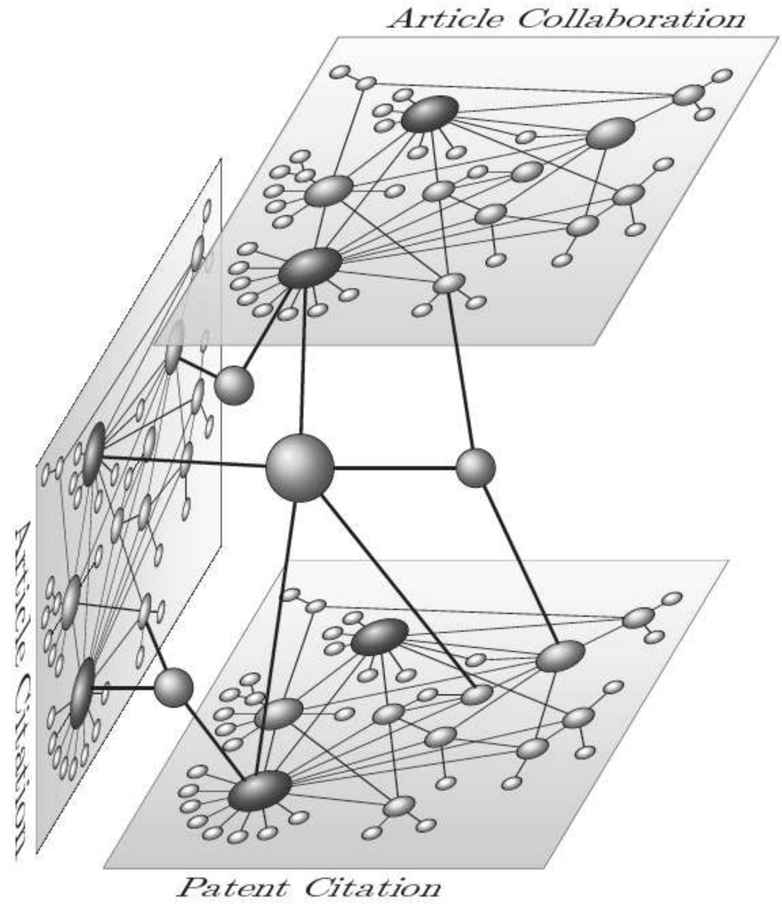
V. THIRD STEP: NETWORK OF NETWORKS

From these 5,347 two-layer nodes (Table 3) now we may further identify 348 three-layer nodes (Table 4).[9]

These three-layer nodes form a special network (see Figure 4) - a network of networks, for they connect all three basic networks (section III) and the networks formed by two-layer nodes (section IV). As a network of networks this set of three-layer nodes have a very special position that defines a hierarchical nature of these international layers of IKLs and that suggests a role for the organization of the innovation systems as a whole.

[9] The algorithm prepared for the data processing (see section II) selected 342 institutions as three-layer nodes. Manually we identified more six more institutions (CAS, Moderna, BioNtech, GlaxoSmithKline, Bristol-Myers and Jansen) in layer#1 that were not matched to their names in layers #2 and #3. These institutions were added to this new network and included in Table 4. This procedure only confirms the observation made in subsection II.1, footnote 3, that at the current phase of our research the overlapping and the multilayer nodes are probably underestimated.

FIGURE 4:
CONNECTING THREE INTERNATIONAL NETWORKS:
INSTITUTIONS THAT ARE PART OF THESE THREE LAYERS
348 multilayer nodes are institutions (78 universities, 2 hospitals, 268 firms)
(2017)



Source: WebOfScience and PatStat, authors' elaboration

V.1. A Description of this Network of Networks

Table 4 summarizes the information regarding this new level. Table 4 shows how this network of networks involves a relatively small share of institutions present in our three basic layers: so far, we have identified 348 three-layer institutions – approximately 0.1% of all nodes identified in our investigation. This network of networks is firm-led, as there are 268 firms out of 348 nodes (77%).

Although only 0.1% of all institutions identified comprise in the three basic networks (section III), these 348 institutions are involved in 5.9% of all scientific papers with cross-border co-authorship, 25.5% of all patents with cross-border patent citations and 23.5% of all patents with cross-border scientific paper citations. These data are an indication of the key role which these institutions play and hint at the hierarchical nature of these networks.

TABLE 4
Data on the Network of the Networks
(Intersection Between the Three Networks of Table 3):
number of three-layer nodes, institutions, participation of in the three basic networks
(2017)

CHARACTERISTIC	Total in this network of networks	% TOTAL of all three basic networks
THREE-LAYER NODES	348	0.1
FIRMS	268	NA
UNIVERS/RES. INST	78(*)	NA
HOSPITALS	2	NA
ART-COL-ART	33,620	5.9
PAT-CITE-PAT	48,235	25.5
PAT-CITE-ART	3,628	23.5

Source: WebOfScience, Patstat - authors' elaboration
NA- Not Available
(*) IMEC and EMPA are included here

These three-layer nodes combine the three different capabilities expressed in our three different IKLs: each three-layer node is simultaneously an important generator of scientific knowledge – as part of international co-authorship in scientific papers -, as well as a creator of technological knowledge condensed in patents that use other patents as input and use scientific papers as input. The capability to simultaneously be in these three parts of innovation might be evidence of previous elaboration on this by Cohen and Levinthal (1989, 1990) and Rosenberg (1990): firms and institutions do research as a way to join broader information networks.

Disaggregating the different institutions that populate this network of networks is useful to investigate the potential innovative labor division within these networks. Table 5 presents data that may help to investigate this issue.

TABLE 5
Ranking of Institutions in the Network of Network, According to Different Layers
(2017)

TABLE 5A
Ten Leading Institutions According to Layer #1

INSTITUTION	COUNTRY	ARTICLES W/ INTER. COAUTHORSHIP	PATENTS W/ INTER. CITATION	PATENTS W/ INTER. ARTICLE
TSINGHUA UNIVERSITY	CN,TW	1.783	103	5
PEKING UNIVERSITY	CN	1.432	9	3
MCGILL UNIVERSITY	CA	1.366	3	1
MONASH UNIVERSITY	AU,MY	1.189	4	2
XIAN JIAOTONG UNIVERSITY	CN	1.148	3	1
FUDAN UNIVERSITY	CN	1.037	5	1
KING SAUD UNIVERSITY	SA,US	1.033	57	4
JOHNS HOPKINS UNIVERSITY	IN,IT,ML,SA,U!	995	2	1
THE REGENTS OF THE UNIVERSITY OF CALIFORNIA - BERKELEY	US	981	47	5
THE REGENTS OF THE UNIVERSITY OF CALIFORNIA - SAN DIEGO	US	971	47	18

TABLE 5B
Ten Leading Institutions According to Layer #2

INSTITUTION	COUNTRY	ARTICLES W/ INTER. COAUTHORSHIP	PATENTS W/ INTER. CITATION	PATENTS W/ INTER. ARTICLE
INTERNATIONAL BUSINESS MACHINES; INTERNATIONAL BUSINESS M	AU,BR,CA,CH,(	249	5.179	366
SAMSUNG ELECTRONICS CO., LTD.; SAMSUNG ELECTRONICS; SAMSI	CN,KR,US	31	4.613	110
QUALCOMM INC.; QUALCOMM INCORPORATED; QUALCOMM, INCC	NL,US	5	1.898	252
APPLE INC.; APPLE, INC.	US	2	1.682	65
INTEL CORPORATION	AT,CN,DE,ES,G	50	1.484	62
LG ELECTRONICS; LG ELECTRONICS INC; LG ELECTRONICS INC.; LG E	KR	3	1.451	33
GOOGLE INC; GOOGLE INC.; GOOGLE, INC.	AU,CA,CN,DE,(	42	1.276	119
SONY CORPORATION	JP	3	1.166	35
GENERAL ELECTRIC COMPANY	CH,IN,SE	4	1.104	37
HUAWEI TECHNOLOGIES CO. LTD.; HUAWEI TECHNOLOGIES CO., LTI	CA,CN,DE,FR,F	39	1.086	123

TABLE 5C
Ten Leading Institutions According to Layer #3

INSTITUTION	COUNTRY	ARTICLES W/ INTER. COAUTHORSHIP	PATENTS W/ INTER. CITATION	PATENTS W/ INTER. ARTICLE
INTERNATIONAL BUSINESS MACHINES; INTERNATIONAL BUSINESS M	AU,BR,CA,CH,(	249	5.179	366
QUALCOMM INC.; QUALCOMM INCORPORATED; QUALCOMM, INCC	NL,US	5	1.898	252
HUAWEI TECHNOLOGIES CO. LTD.; HUAWEI TECHNOLOGIES CO., LTI	CA,CN,DE,FR,F	39	1.086	123
GOOGLE INC; GOOGLE INC.; GOOGLE, INC.	AU,CA,CN,DE,(	42	1.276	119
SAMSUNG ELECTRONICS CO., LTD.; SAMSUNG ELECTRONICS; SAMSI	CN,KR,US	31	4.613	110
AT & T INTELLECTUAL PROPERTY, I, L.P.; AT&T INTELLECTUAL PROPE	US	10	661	105
SEMICONDUCTOR ENERGY LABORATORY CO., LTD.; SEMICONDUCT	JP	2	935	99
TELEFONAKTIEBOLAGET L M ERICSSON (PUBL); TELEFONAKTIEBOLA(	ES,IL,SE	7	1.043	71
APPLE INC.; APPLE, INC.	US	2	1.682	65
CISCO TECHNOLOGY INC.; CISCO TECHNOLOGY, INC; CISCO TECHNC	CH,ES,IN,NO,U	19	489	64

Source: WebOfScience, Patstat - authors' elaboration

Table 5 has been organized to examine the position of each three-layer node in the three different basic networks – sign for these differentiated predominant roles in innovation systems. As may be seen, Table 5 is organized in three parts, each dealing with rankings from different layers.

Table 5A shows the ten leading institutions in a ranking organized by their participation in layer #1. As layer #1 is a university-led network, all ten leading institutions are universities. Checking these institutions with a ranking prepared by Nature Index (2021) for Academic Institutions, all these ten leading institutions in Table 5A are on the list for 2018, although in different positions – Peking University is in 8th position, University of California, Berkeley, is in the 6th position and Xian Jiaotong University in the 130th position. The first firm in this ranking is IBM, in the 42nd position.

Table 5B shows the ten leading institutions in a ranking organized by their participation in layer #2. As layer #2 is a firm-led network, as expected, all ten leading institutions are firms. Checking with the Nature Index (2021) ranking for Corporate Institutions, five of these firms in Table 5B are on the list for 2018 (IBM, Samsung, Intel, Google and Sony). If we look for the ten leading firms in the Nature Index for 2018, nine of them are in this network of networks (GNS Science is the only firm that is not in our network of networks, but it is in layer #1). The first university in our network of networks, in this ranking according to layer #2, is TSINGHUA UNIVERSITY, in the 69th position.

Table 5C shows the ten leading institutions in a ranking organized by their participation in layer #3. As layer #3 is a firm-led network, once again, all ten leading institutions are firms. There are 6 firms both in Table 5B and 5C: an indication of similarities between these two networks. The first university in our network of networks, in this ranking according to layer #3, is NORTHWESTERN UNIVERSITY, in the 19th position.

These data suggest that different institutions may have different positions of proximity to the three different basic networks. These different proximities may be another indication of the asymmetric nature of the networks: IBM has inherently greater approximation to layers #2 and #3 than University of California, which is nearer layer #1.

Since we are investigating a firm-led network (of networks), there are at least two different types of firms populating this network. On the one hand, there are large and established firms, exemplified by IBM, Hoffman-La Roche, GE Electric, Robert Bosch – that built their innovative and learning capabilities in long-term processes. While, on the other hand, there are very young firms, exemplified by BioNtech (founded in 2008), Moderna (founded in 2010), Carcassia Ltd (founded in 2006) and Otosense (founded in 2013) – firms that were created already as well-connected institutions, with links to universities and other firms that generated their own IKLs in 2017. These young firms might suggest a way – a route, if you will - to take advantage of these international layers to grow and innovate.

The set of firms in this network of network may also suggest that some sectoral systems of innovation may have strong international linkages, shown by their presence in this network of networks. A very preliminary search to match the 268 three-layer nodes that are firms with their NACE classification identified 193 firms in our ORBIS database. This very preliminary identification shows the leading NACE sectors: 1) NACE 26 "Manufacture of computer, electronic and optical products" - with 46 firms matched - 2) NACE 21 – "Manufacture of basic pharmaceutical products and pharmaceutical preparations" – with 30 firms matched; 3) NACE 72 – "Scientific research and development" – with 19 firms matched (within this sector, there is a subsector NACE 7211 – "Research and experimental development on biotechnology" – with 12 firms matched); 4) NACE 20 – "Manufacture of chemicals and chemical products" – with 17 firms matched; 5) NACE 28 – "Manufacture of machinery and equipment n.e.c." – with 9 firms matched; 6) NACE 58 – "Publishing activities" – with 9 firms matched; 7) NACE 62 – "Computer programming, consultancy and related activities" – with 9 firms matched. At least in sectors like these, the long-term survival and initial and/or persistent growth of firms seems to depend upon a heavy and simultaneous insertion in those three international layers.

V.2. What Multiplex Network is this?

After describing the key features of these three basic networks (section III), how they overlap (section IV) and how they form a network of networks (sub-section V.1), we may evaluate what type of network is this. Specifically, we may try to describe some of its basic properties, based on the referenced concept of multiplex networks as presented in literature reviewed (section I): multilayered networks that have layers with different sizes and with not all nodes participating in all layers. As we presented in Table 4, there is a small subset of three-layer nodes that overlap and intersect with all networks, an asymmetrical structure that shapes these networks as self-organized systems (see Table 2).

With this structure of three basic layers with multilayer hubs and nodes as presented in Figure 4, we may return to Kivelä et al (2014, pp. 206-207) and check our previous identification of this network as a multiplex network. Kivelä et al (2014, p. 206) proposes a typology of networks that involve different properties: 1) “Is the network node-aligned?”, 2) “Is the network layer-disjoint?”, 3) “Do all layers have the same number of nodes?”, 4) “Are the couplings diagonal?”, 5) “Do inter-layer couplings consist of layer couplings?”, 6) “Are the inter-layer couplings categorical?”.[10] A preliminary analysis of this multilayer network shows that 1) it is not node-aligned, 2) it is not layer-disjoint, 3) each layer has a different number of nodes, 4) the couplings are diagonal, 5) the inter-layer couplings consist of layer couplings, and 6) the inter-layer couplings are not categorical.

Furthermore, in relation to one feature of multiplex networks, “correlated multiplexity”, we did not find in our networks the pattern of correlated multiplexity that is “most frequent” (Lee et al, 2014, p. 55): the positively correlated multiplexity. As the data presented in Table 5 show, the “node with large degree in one layer” does not necessarily have “more links in other layers”. The different rankings in Tables 5A and both Tables 5B and 5C, show that a large degree in layer #1 does not replicate in layers #2 and #3.

This very tentative and preliminary analysis of properties of our network show how peculiar it is – a complicated network, showing a non-symmetric hierarchical structure. [11] Since each of its component layers show power-law properties and self-organization properties, we may conclude that their overlapping preserves their self-organized properties.

VI. CONCLUDING REMARKS

The contribution of this paper starts with the choice of the unit of analysis: an international knowledge link (IKL), a knowledge flow that leaves a trace and connects two nodes in different countries. The second contribution is the choice of the nodes for this analysis: institutions – firms, universities or research institutes that host paper’s authors or patent’s inventors. These IKLs form layers, depending on the nature of their type – layer #1, a university-led network formed by international collaboration in science, layer #2, a firm-led network formed by international citations of patents and layer #3, a firm-led network formed by international citations of scientific papers by patents. Our database prepared with data from 2017 identifying 17,240,834 IKLs distributed in these three layers.

The nodes connected by these IKLs are institutions: a definition that enables our analysis to integrate these three different layers, forming three self-organized networks. Following a conjecture that we are investigating multilayered networks, the first step of our investigation is the identification of 307,351 nodes in the three basic layers, the second step the identification of 5,347 two-layer nodes and the third step the mapping of 348 three-layer nodes – thus, a network of networks. The overlapping of these three networks by these multilayered nodes shapes a very peculiar and asymmetric network.

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[10] Kivelä et al (2014, p. 271) explains each property.

[11] As we discussed in a previous paper (Ribeiro et al, 2017) on how capitalism is a complex system with very peculiar properties, which distinguish it from other complex systems of the physical and biological worlds, consistent with Goldenfeld and Kadanov (1999). In the realm of networks, it also seems that contemporary economy shows very peculiar structures of networks. A theme that deserves further discussion.

The power-law properties of the three basic networks - fingerprints of self-organization – suggest that these networks are resilient and we surmise that the network of networks formed by their overlapping might preserve these self-organized properties. The structural properties of these networks of IKLs are evidence that in contemporary innovation systems there are more than simple international connections between different national systems of innovation, but layers of international knowledge links that form new levels of innovation systems.

This empirical finding – international layers in innovation systems – has theoretical implications. Layers in the analysis of innovation systems were suggested by Binz et al (2017), which pioneered an interpretation of innovation systems as multilayer structures, including global innovation systems. Our findings – the three basic networks organized from IKLs – dissect the contemporary structures of innovation systems, showing layers that are international.

The first implication of our identification of international layers is to understand that they are connected with domestic, regional and local networks integrated by firms and universities without direct participation in international knowledge flows. Although without direct connections to these international flows, they can be indirectly connected, as they establish a local connection with an institution that is part of one of our basic three networks. On the one hand, this may improve absorptive capabilities of local firms and research institutions – as they may learn with institutions internationally connected. On the other hand, this broadens the scope of institutions that populate the international layers, because a contact with a local institution may be a source of new learning and new knowledge.

A second implication is the identification of structural changes in innovation systems: there was a phase when countries were firstly connected and then tensioned by international flows. Now, with the reality of international layers, their organization and the role performed by 348 three-layer nodes at their core suggest that the dynamic of innovation at this phase is dependent on a well-connected position in these international layers. There are institutions that live and operate at these international layers – and there is some evidence that this population is growing. In the language of complex systems, our analysis has shown new structures – international layers of IKLs – that, once they were created and began to grow, they triggered processes that feedback upon the whole system. Therefore, we may have evidence of structural change within innovation systems.

A third implication is about the nature of the innovative firm – old and long established or young and growing, the innovative firm have big incentives to be located in these international layers. An innovative firm needs to be in a place where it can be aware of knowledge flows that support innovation, and to join the ranks of these international layers is a step in the direction of the two sides of innovation – innovating and learning.

A fourth implication is related to sectoral innovation systems: a very preliminary sectoral analysis of firms that are at the network of networks (firms that are part of these 348 three-layer nodes) suggests that there may be sectoral systems of innovation that are truly international.

A final question, certainly more speculative, is related to evidence of global systems of innovation (Binz et al, 2017) – are these international layers, their intertwinement and the network of networks sufficiently identified in this paper enough to provide further support to this new level of innovation systems? In a previous paper (Britto et al, 2021) we reviewed the literature, focusing on three forces that might be shaping a new layer in innovation systems – 1) spread and growth of transnational corporations, 2) the internationalization of science, and 3) the new information and communication technologies are infrastructures for knowledge flows. The empirical evidence organized in this paper joins researchers that have been suggesting that it is time to discuss this new institutional form, a new structure in innovation systems – an international level -, that could reorganize the overall organization of innovation systems, with the emergence of new hierarchy that organize local, regional, sectoral and national systems.

The emergence of an international system of innovation is a topic that merits further research, within an agenda that could include other issues that were mentioned in this paper: 1) an investigation on the properties of this network of networks according to network science – since this network seems to be very peculiar vis-à-vis the cases discussed in the literature; 2) an investigation of how these international layers connect with national and local layers of innovation systems – very broad networks that although not directly international may easily have international connections taking advantage of small world properties of these international networks; 3) an investigation to understand the inter-temporal behavior of these basic networks and their overlapping.

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