Challenges in Measuring and Capturing Scientific Knowledge in the Emerging Nanosciences

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***Abstract*—A key challenge in the sciences is the quantification, measure and management of knowledge, particularly as it relates to the growth and emergence of new disciplines. This exploratory study examines the growth of two relatively new sciences: nanotechnology and nanomedicine. Using a simple analysis of the growth of publications in these two related fields, the authors show that the growth in new sciences has been quite rapid. Nevertheless, a major limitation of this work is that it is far too difficult to quantify their spillover effects and new methods of quantifying these. The authors propose that new ways of quantifying scientific spillovers is needed and require investigation, given the limitations of scientific metrics such as bibliometrics.**

***Index Terms*—Knowledge transfers, bibliometrics, interdisciplinarity.**

I. Introduction

Knowledge and its transfer is a crucial component to the development of societies and has been the central component to the rise of the global knowledge economy in the last four decades [1]. The strongest rate of knowledge growth in the world began to be seen during the industrial revolution as a result of the rapid expansion of mechanization and industrialization of economic activities [2]. More recently, during the last forty years or so, the world has experienced a pronounced transformation resulting from the rise of the global knowledge economy. This innovative form of doing business is emerging from two defining forces. The first is the rise in knowledge intensification of economic activity and the increasing globalization of economic affairs [1]. Four pillars have been identified as being the key requisites for countries and regions to participate in the global economy, namely, education and training, information infrastructure, economic incentive and a sound institutional regime and sound innovation systems, which assists in the creation of new knowledge [2]. Central to this discussion, however, is how best to manage and measure knowledge creation in the 'knowledge based economy'[5].

A key challenge is the quantification, measure and management of knowledge, particularly as it relates to science. Thus, this exploratory paper examines and discusses the following themes. In the literature review, we critically discuss some of the current limitations to measuring and quantifying knowledge. In addressing this issue, Section III of this paper proposes a methodology for measuring knowledge in three separate but related knowledge fields. Section IV discusses the data and methodology used to quantify knowledge and presents three case studies of how these measures are actually applied in understanding the growth in the stock of knowledge. The final section provides a conclusion and discusses ideas for future research.

II. Literature Review

Two crucial forces are defining and shaping the knowledge economy: the rise in knowledge intensity of economic activities, and the increasing globalisation of economic affairs [1]. A particular feature of knowledge is that it is an intangible and an abstract good, however, it can be appropriated by anyone who can actually make a use of it. In economic terms, knowledge is at the centre of value creation, productivity and economic growth [1]. Embedded in these two forces are two crucial components, capability of learning and innovation [3]. A key benefit of knowledge creation in nations is that it assists in their economic and social development. However, the knowelege economy is made up of different fragmentary knowledge economies, which exist for three reasons. Firstly, the existence of disequilibrium and social imbalance; secondly, collaborative economic action; and finally the systemic nature of strategic competitiveness [3].

The idea of disequilibrium and social imbalance originates with Schumpeter but was dialectically adopted by the post Schumpeterian innovation theorists. Briefly explained where development occurs, the core innovation causes a systemic shock increasing the disequilibrium of the economy in question which is followed by the appearance of new market niches.

Collaborative economies refer to the pattern and development of interorganizational collaborations as a result of self-sustaining dynamic processes in which initial research relationships trigger the development of experience at orchestrating alliances. The systemic nature of strategic competitiveness relates to the ability to co-create changes. The rapid responsiveness of an organization to changes depends on its sensibility to the events in the environment (the ability to quickly perceive and understand changes in the environment), and its flexibility (the ability of fast internal transformation) [3].

According to the World Bank, a country requires four pillars in order to achieve development. These four pillars place particular importance on the following key elements. First is the importance of an educated and skilled population in order to create, share and use knowledge. This involves the improvement of the human capital of a nation by creating solid and equitable educational institutions.

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Secondly, a nation requires a dynamic and evolving information infrastructure, ranging from radio to the internet, to facilitate the effective communication, dissemination and processing of information. The third pillar consists of a regulatory and economic framework that enables the free flow of knowledge and encourages entrepreneurship at all levels of the economy in order to create a vibrant and solid society. Finally, a network of research centres, universities, think tanks, private enterprises and community groups is necessary to tap into the growing stock knowledge, assimilate and adapt it to local needs, and create new knowledge [2]. Trying to measure knowledge and knowledge diffusion is one of the most difficult challenges faced by scientists and policy makers [6].

The knowledge infrastructure of an economy can be viewed in terms of the networked relations among universities, industries and governmental agencies [7]. While both the links and the nodes of the networks can be measured by using various indicators (e.g., patents, hyperlinks, citations), the knowledge base can be considered as a result of the interacting fluxes of communications through these networks [6], [7].

In order to measure and quantify knowledge, a number of approaches have been adopted. Leydersdoff and Scharnhorst [9] and Leydersdoff [6] catalogue a very general set of indicators for measuring the knowledge base of an economy. This set of indicators illustrated below shows how knowledge is measured in three different fields of economic endeavour, namely, science, technology and innovation, using science citation indices, patent data bases and various forms of market data.

III. The Emerging Sciences

Before the Second World War each science owned its own turf. Mode 1 of knowledge production as identified by Gibbons *et al.* [10] was preponderant in all sciences with the following characteristics:

- Hegemony of theoretical or experimental science;
- Internally driven taxonomy of disciplines;
- Autonomy of scientists and their host institutions;
- Monodisciplinary.

The trends gained momentum in the 1980s and generally were driven by:

- The steering of research priorities;
- The commercialization of research;
- The accountability of science.

One may ask how these trends are connected to the growth of interdisciplinarity. The answer is that they led to changes in practice and have given rise to new discourses in science and research. When the researchers had to solve complex problems and meet social and economic needs, new scientific networks appeared, some that faced dramatic changes over a short period of time. Those are the ones which laid the foundation for interdisciplinary fields.

The most widely known model of science is Kuhn's [11] Structure of Scientific Revolutions in which science is characterized by transitions from normal science to science in crisis and from crisis to scientific revolutions. In strict definition, a revolution is when old ideas are discarded in favour of new ones or are dialectically transformed. So when we ask ourselves how to transfer or increase knowledge we should first of all think of science.

If the trend is towards the unification of sciences – and technology – then it comes after a long period of fragmentation that may be seen as a necessary stage for the specific development of each field, at least up to the paradigmatic phase. Theoretical maturity in each science brought along, or was paralleled by, the development of modern technologies that served as bridges among them. More importantly, practitioners – the carriers of specialized knowledge, theoretical traditions and structures specific to a particular field – had to interact and cooperate to solve common problems, and in the process they exchanged quanta of knowledge. What is essential and obvious for science and technology is the difference between the specific mechanisms for the production of knowledge. Science seems to rely more on an organized knowledge production, while technology relies more on a heuristic knowledge.

The main characteristic of newly emerging fields is an increasing synergy between disciplines, which leads to several types of communications between them. With the increasing of the interdisciplinary intensity, the border between knowledge production and knowledge transfer between disciplines begins to be blurred. Moreover, in the case of 'deep' transdisciplinarity, the knowledge production might be just – at least in part – another form of knowledge transfer from one field to another. Finally, knowledge transfer is a 'cheaper' alternative to knowledge production, as the only requirement is the permeability of interdisciplinary borders, which is achievable in large part through appropriate policies. As such, and without minimizing the importance of knowledge production which is the long-term generator of knowledge, the study of knowledge transfer could provide a higher return on investment. It may no longer be viable to conceptualize knowledge application as separable from knowledge production. Yet the implications of this presumption will impact on: the concepts such as 'dissemination', 'technology transfer' and 'recontextualization'; the distinction between academic and 'everyday' knowledge, or between theory and practice, e.g. 'discursive practice'; alternatives to essentialist and instrumental definitions of disciplines and disciplinary boundaries; interdisciplinarity and hybrid knowledge; and the construction of new identities and subjects.

Cross-fertilization between scientific fields is known to produce new developments and innovative products. Multidisciplinarity and interdisciplinarity have been strongly encouraged in the past decade after public acknowledgement of the important role played by the adoption of physical sciences techniques in biology or the use of statistical physics in social sciences. Notable examples of in-betweeners are bioengineering, nanobiotechnology and nanomedicine.

IV. Data and Methodology

The data used in this study is bibliometric data obtained from Scopus. Bibliometrics is a measurement of the impact of (scientific) publications. It has a variety of applications in many different scientific fields. In fact, many research fields use bibliometric methods to explore their scientific impact. According to De Bellis [12], bibliometrics is a methodology encompassing a variety of techniques designed to quantify and analyse the impact of scientific and technological fields, in terms of publications. The most common methods in this discipline are citation and content analysis. In the analysis of three industries that follows, data are obtained from Scopus, the largest abstract and citation database of peer-reviewed research literature. With over 19,000 titles from more than 5,000 international publishers, Scopus offers researchers a quick, easy and comprehensive resource to support their research needs in the scientific, technical, medical and social sciences fields and arts and humanities. It contains more than 47 million records, including 26 million with references back to 1996 (of which 78% include references); 21 million records pre-1996 which go back as far as 1823; 4.9 million conference papers from proceedings and journals; and "Articles-in-Press" from over 3,850 journals [13].

V. Findings

The analysis presented covers two scientific areas, namely, nanotechnology and nanomedicine. Nanotechnology is a new field with broader applications than any other field. It is an enabling technology comparable with microelectronics and as such expected to affect fields as varied as mineralogy, medicine, chemical engineering, electronics, manufacturing and pharmaceuticals. It is most of all a typical Mode 2 of knowledge production and has the following properties: problem oriented;transdisciplinary; subject to accountability; and socially distributed [10].

By using Scopus we can find the numbers of publications in nanotechnology and the growth curve. As nanotechnology is a growing field and a relatively new one, we expected some significant difference between 2000 and 2010. In order to obtain an accurate picture we have used two year intervals for quantifying the publication output.

We use as a first sample the years 2000 and 2001. This period will be later compared with 2009 and 2010. For the beginning of the decade and the end of the decade we calculated the same variables:

- All publications in each of the three chosen fields;
- Proper publications (articles and reviews) for each of the three chosen fields; and field representation.

Between 2000 and 2001 there were 947 proper publications (articles and reviews) listed in the Scopus database, spread over more than 50 publication sources. The sources that published more than 10 articles in nanotechnology were 14. Listed according to the number of citations, 71 articles were cited more than 100 times. A closer look at the main sources in which these articles were published indicates that the field of physical sciences was prevalent. This is consistent with the general literature on the beginning and the evolution of nanotechnology. The subject areas indicate the same. As a growing field, the pattern of publishing in nanotechnology grew significantly throughout the decade. The total number of proper publications in 2009 and 2010 was 6,127. Some of this growth might also come from the more frequent use of the term 'nanotechnology', now describing a field in its own right. Total number of publications (nanotechnology) listed in Scopus in 2000 and 2001 is 1,419. The number of patents is 96. About 423 articles did not qualify as proper publications but were explicit/codified enough to be published.

Nanomedicine took off as a discipline around 2000 and it has been growing since at an exponential rate. However, many of the publications listed by Scopus under nanomedicine are also part of traditional fields such as biochemistry, biology or medicine. The growth of nanomedicine is mostly from within the medical field. To gain a better understanding of the dynamics of evolving fields, in this case, nanomedicine, we are looking at the publication output and the growth of the field. Scopus results show that between 2000 and 2010 there were 1,839 publications in nanomedicine, with 1,355 proper papers. In only 10 years the number of publications alone grew from a base of a handful of publications to nearly 2,000. This indicates the massive growth of this field in a very short relative period of time.

VI. Conclusion

This exploratory paper has looked at the growth of knowledge production and transfer in two specific fields, namely nanomedicine and nanotechnology, by using data from Scopus. The trends observed are as follows.

Knowledge growth and the growth in number of publications are quite sharp in a relatively short period of time.

While the number of published papers grows very fast, it is unlikely that scientific knowledge grows at the same rate, as it is difficult to capture the extent of spillover effects within and outside the two fields under consideration.

As a result of the above limitation of capturing spillover effects of knowledge growth, there is a need to investigate new ways of capturing knowledge growth in new disciplines. While databases such as Scopus offer a glimpse to the growth of new sciences such as nanotechnology and nanomedicine, new means of capturing spillovers are required in order to quantify their real impact on the economy, society and indeed their respective sciences.

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