Between Technology and Science:
Exploring an Emerging Field:
Knowledge Flows and Networking on the Nano-scale

by

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BETWEEN TECHNOLOGY AND SCIENCE
EXPLORING AN EMERGING FIELD

KNOWLEDGE FLOWS AND NETWORKING ON THE NANO-SCALE

D.Phil. Thesis

SPRU – Science and Technology Policy Research
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Abstract

This dissertation addresses emerging developer communities in a new field of science and technology as well as methods to capture exchange processes between them. It contributes to the discussion about a new mode of knowledge production and a changing division of labour between public research, industry, and government by investigating 'nanotechnology' – an emerging area between science and technology. To explore exchange processes in this field, the study applies various methods. In particular, it uses patent citation analysis.

The methodological contribution is a new interpretation of this indicator, which sees patent citations as information flows that point to reciprocal exchange processes and potential overlaps between science and technology. This is in contrast to the received interpretation, which suffers from the application of a framework that was developed in the context of scholarly citation and does not fully appreciate that a patent citation is established by the patent examiner – a party external to the inventive process.

Various formats of patent citation analysis describe 'nanotechnology' as a set of instrument-driven scientific fields on their way towards science-related technologies. Even though nanotechnology patents contain more patent citations to the scientific literature than other technical fields, the science and technology systems are relatively autonomous. What links them in the case of nano-science and technology is a common interest in improving techniques of nano-scale measurement and manipulation.

Another finding is that both countries and firms exhibit relatively strong path-dependencies. While nanotechnology comprises a key set of technological areas – instrumentation, electronics, and pharmaceuticals/chemicals – nano-scale activities vary considerably from country to country. Also knowledge-building activities of firms follow a strong technological path-dependency. As a result, 'social capital' seems to be confined to chiefly technological or scientific trajectories. Hence, 'social capital' appears not to be very useful in explaining how knowledge is accumulated and integrated at the nano-scale.

Given the central role of instrumentation and the mediated nature of exchange between science and technology at the nano-scale, public policies should be directed towards supporting education and infrastructure in the area rather than more 'direct' transfer mechanisms.

Table of Contents

Table of Exhibits

PART I:

FOUNDATION AND FRAMEWORK FOR ANALYSIS

Chapter 1 - *INTRODUCTION*

1.1 Objectives and Background

The subject of this thesis is technologies emerging in the context of science-based innovation. This study investigates the relationships between particular factors that determine how actors enter and explore new science and technology. It contributes to the body of knowledge addressing issues, such as: How do new fields between science and technology emerge? What impact do path-dependencies and networks of organisations have on their emergence? How do nation states influence 'technological choice' under uncertainty? How can one track the evolution of developer communities?

In particular, the thesis addresses the question: How do actors access and integrate new knowledge in emerging and science-related fields? In new technologies, actors face a high level of uncertainty. Often the borderlines of the new paradigm are not drawn yet. Networks are either not formed or are still being formed. A process of trial-and-error search goes on, at the same time that investing in commercial products has begun. Due to the paradox that while uncertainty makes ventures risky, high risk is often associated with high rewards,[1] corporations face appraisal dilemmas in new technological fields.[2]

Nanotechnology was chosen as the subject of this study because it is a field where actors may experience difficulty in evaluating technological options for the reasons mentioned above. Many companies have begun to explore the

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1 Brealey, R.A.; Myers, S.C. (1996). Principles of corporate finance. New York: McGraw-Hill; part 6.

2 This is indicated by the growing management literature on options evaluation. See in particular the works by Mitchell and Hamilton, for instance, Hamilton, W.F. (1990). The dynamics of technology and strategy. European Journal of Operations Research, 47, 141-152. Mitchell, G.R. (1990). Alternative frameworks for technology strategy. European Journal of Operational Research, 47, 153-161. Mitchell, G.R.; Hamilton, W.F. (1988). Managing R&D as a strategic option. Research-Technology Management, 31 (3), 15-22. Also, see Myers, S.C. (1984). Finance theory and financial strategy. Interfaces, 14, 126-137.

underlying scientific aspects of nanotechnology; some firms have even invested in certain nano-scale techniques and processes. However, nanotechnology is at the early stage of its development. Therefore, there is no generally accepted definition.

For the purposes of this thesis, nanotechnology is defined as a cluster of scientific and technological activities where functional structures with dimensions or tolerances in the nanometre (0.1 to 100 nm) level play a critical role. Nanotechnology comprises those fields of technology that help to study, observe or manipulate structures at the nano-scale[3] as well as objects or projects whose novel properties derive from their nanometre-scale.[4] Electronics, materials and instrumentation are potential fields of application for nanotechnology. Companies in these fields are currently exploring nano-scale technologies. Foresight studies predict, moreover, that developments in nanotechnology will affect large parts of the manufacturing economy.

Traditionally, there has been an institutionalised division of labour between publicly funded scientific research in the university sector and privately funded technological development in industry. However, this division of labour is undergoing a dramatic change – in particular, because universities are increasingly assuming a role in developing and commercialising new technologies. Science policy analysts, most notably Gibbons and his colleagues, believe they are witnessing a shift towards a new mode of knowledge production, which they call 'Mode 2' for lack of a better term. In

[3] This includes in particular advanced instrumentation, such as the Scanning Tunneling Microscope (STM) and the Atomic Force Microscope (AFM) as well as a number of advanced thin-film growing techniques.

[4] A growing number of nanostructured powders and pigments are being commercialized especially in the US. Materials for semiconductors and molecular electronics are said to be

particular, this mode is characterised by 'transdisciplinary' collaboration in transient organisations of both industrial and academic actors.[5] Gibbons et al. suggest that this new approach of knowledge production ('*Mode 2*') is replacing the traditional type of knowledge generation ('*Mode 1*'). While Mode 1 is described as disciplinary, located in well-established sites and far away from an application context, Mode 2 is depicted as

> "distinctly applied in character, transdisciplinary in its fundamental research orientations, pursued by heterogeneous and transient research collective[s] and both socially accountable and inherently reflexive in its contents and research methods. The new mode of knowledge production is typically observed in innovative research fields such as new materials, biogenetics and information technology."[6]

Because of the lack of comprehensive empirical studies of knowledge production phenomena, Modes 1 and 2 appear in this context to be the only alternatives as to how knowledge production can be organised. An 'either/or' seems to dominate the discussion. This raises the question how useful the ideas related to Mode 2, or a new mode of knowledge production, really are. However, instead of rejecting the model entirely, it might be useful to investigate the world that lies between the two modes.

In the study of university-industry-government interrelationships, these new developments are often referred to as the 'triple helix'.[7] To develop new technologies, universities, industry, and government- formerly the occupants

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of particular importance.

5 Gibbons, M.; et al. (1994). The new production of knowledge. London: Sage.

6 Wilts, A. (2000). Forms of research organisation and their responsiveness to external goal setting. Research Policy, 29, 767-781, here 768.

7 Etzkowitz, H.; Leydesdorff, L. (eds) (1997). Universities and the global knowledge economy:

of relatively separate and distinct institutional spheres- are now assuming tasks in the development that were originally in each other's domains.[8] This is the case especially in the field of so-called science-based technologies, an area of growing economic importance where industrial technology relies heavily on scientific results from universities and other research organisations.[9] This research investigates the specific forms of the new division of labour in a novel area that is about to become a science-related field of technology.

The following section of this chapter will first outline the relevance of this study before the backdrop of previous work on emerging technologies and community evolution. Then fundamental assumptions about the nature of developer communities and their members are clarified and the term novelty is defined. This section also specifies the contributions to knowledge that this thesis makes. Finally, the general research design and structure of the study are presented.

1.2 Relevance

This section illustrates why it is relevant to study how new fields and communities of scientists and technologists evolve. Surprisingly, there is little literature on the underlying factors that shape the emergence of a developer community. Most of the models presented appear to be essentially sequential and descriptive, or they focus on the evolution of existing networks, not on emerging communities and fields. Yet these models do not elucidate the

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a triple helix of university-industry-government. London: Pinter.
[8] Ibid.
[9] Narin, F.; et al. (1997). The increasing linkage between U.S. technology and public science. Research Policy, 26 (3) 317-330, and literature therein.

driving factors that determine the way in which actors explore new science and technology. Nor do they explain how this type of knowledge building is related to the development of networks and the emergence of a new scientific and technological community. Two examples may illustrate this.

For instance, Debackere and Rappa discuss community networks evolving in relation to the emergence of a new technological paradigm. These authors characterise the typical early stages of a successful new paradigm as 'bootlegging' and 'bandwagon'. During the bootlegging period, which may last for a long time, a handful of researchers dedicate themselves to furthering the field, even though their enthusiasm may not be shared by their peers but severely criticised. Typically, they have difficulties in securing adequate funding; hence, the term 'bootlegging'. Characteristically, a few isolated individuals start working on similar problems with roughly similar ideas.[10]

Researchers dedicated to a new and unorthodox field of inquiry are confronted with a difficult dilemma. On one hand, before receiving resources, they need proof that their work will yield results. On the other hand, without resources, they are unable to do that. 'Bootlegging' enables fledging research to proceed without being scrutinised by managers and other researchers, up to a point at which the idea starts to look promising. During this phase, then, the community consists of only a few organisations, and only a fairly modest number of researchers join its ranks every year.[11]

As the number of individuals working on the same problem area increases, a communication network emerges with ties that are much stronger

[10] Debackere, K.; Rappa, M. (1994). Science and industry: network theory and paradigms. Technology Analysis and Strategic Management, 6 (1) 21-37, here 27-28

than the ties binding the individuals to the organisations they formally belong to. In the course of this so-called bandwagon phase the number of researchers belonging to the community increases rapidly. As the community grows, a new paradigm comes into being, which is seen by the higher-level network of the (sub-) discipline as competing with older paradigms. The community tries to organise congresses and start journals in order to steer the selection process. The R&D community is typically distributed across organisations, sectors, and countries. If the work of a new community seems interesting from a commercial point of view, some scientists are recruited by enterprises, while those who already work within industry are allowed to devote their efforts openly to the new field. Also, some scientists may decide to become entrepreneurs themselves.

While this model gives an accurate account of how a developer community emerges at the interface between science and technology, it says very little about the underlying factors that shape an emerging field. It does not provide answers to the crucial 'who', 'what' and 'why' questions related to a specific field of science or technology.

Unfortunately, social-constructivist approaches are not much more instructive. They often focus on learning or knowledge acquisition in an established context of existing communities. An example of this is Tuomi's notion of learning trajectories. He focuses on how a 'novice' enters a community and becomes a legitimate member following a 'trajectory of learning'. According to Tuomi, the beginner gradually adopts knowledge and practices of a given community up to the point where s/he will have reached

[11] Ibid.

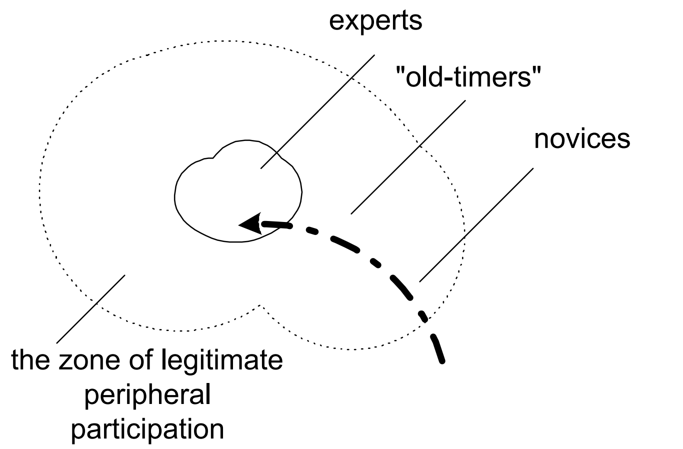
the position of an expert. This development is related to a process of learning. In the beginning, the newcomer is tolerated by the other members of the community as a 'peripheral participant', "who can barely make sense of the discourse within the community."[12] As the novice familiarises him/herself with the 'conceptual systems' of the community and subscribes to certain positions and commits to specific interpretations, he/she begins to take part in the activities and exchanges of the community. As a result, his or her understanding of the field develops further. As a community member, he or she can understand the positions of their peers and is knowledgeable enough to argue points of view. This leads to yet another, higher level of cognitive ability since a member of the community needs to manage both internal and external points of view simultaneously. Eventually, the new member of the community reaches the cognitive level of an expert who, in Tuomi's words, can "not only understand […] the various points of view within a community, but also grasps the ability of the owners of these views to develop them."

However, in the context of this study, it is important to be aware of the assumption that underlies this model of learning. Tuomi implicitly assumes that there is a community of practice that a 'novice' can 'enter'. What one can find tracing the emergence of a novel field of technology is not *a* community of practice where novices can 'join the club' of experts and 'old-timers', but a *multiplicity* of communities of practice. Some members (including the senior

[12] Tuomi, I. (1999). Inside innovation clusters: collective knowledge creation in networks and communities. In Schienstock, G.; Kuusi, O. (eds). Transformation towards a learning economy. Helsinki: Sitra, 143-157. Cited after draft, 8-9.

ones) are pursuing activities directed at creating a 'new zone of legitimate (peripheral) participation', i.e., a community in which they are all novices.[13]

Exhibit 1-1. Trajectory of learning in a community of practice.



The concepts discussed above are useful in describing how existing communities adopt new members (as in the Tuomi model) or in a general way depicting how communities evolve (as in the case of Debackere and Rappa). However, neither of these concepts explains the factors that shape the co-evolution of networks and technologies in their early stages. Other studies have focused more explicitly on how technology and network develop in relation to each other. However, this has usually been done within the context of an established industry.[14]

[13] To illustrate this situation, one would need to multiply the zone depicted in Exhibit 1-1. The trajectories of learning, which are illustrated by an arrow leading into the center of the community of practice in the exhibit, would now be directed leading away from the familiar center towards a fictive, not yet existing one. This center is the focal point of a new community of practice that has not fully come into being yet. Even though Tuomi's model does not directly apply to this context, it helps us understand why the formation of new technologies and communities of practice is a long and laborious process. It links the idea of a technological or industrial path of development with existing networks of personal and organisational contacts that are influential when novel fields are to be explored.

[14] Rosenkopf, L.; Tushman, M.L. (1998). The coevolution of community networks and technology: Lessons from the flight simulation industry. Industrial and Corporate Change, 7 (2), 311-346.

So far these phenomena have not been studied from the point of view of the emerging field itself. Such a view is important if one deals with cross-sectoral technologies that have a strong relation to novel sciences. Practitioners in S&T policy often try to plan and administrate technology-centred programs, but need to rely on industry-level information only. For these reasons, it is important to study the factors that either facilitate or obstruct a new area's transition from the bootlegging to the bandwagon stage, and to do so by adopting the perspective of the novel field itself.

1.3 Fundamental Assumptions

This thesis deals with factors that have an impact on the 'division of labour' in a new field of science and technology. Even though this research is context-driven, it is built upon a number of fundamental assumptions. It is not entirely free of any preconceptions about developer communities, their members and how they interact in a systems environment. In particular, developers are viewed as heterogeneous[15], resource-dependent and capable of learning. This research also assumes at the outset that developer communities are components of complex socio-technical systems. Furthermore, since this research discusses the emergence of new fields of science and technology, novelty needs to be defined in the context of this study. Finally, the notion of developer communities is defined and related to the broader discussion on the topic. This section clarifies in more detail the basic ideas that this thesis takes as its points of departure.

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[15] The term 'heterogeneous' in this context means differing in structure, quality, etc.; dissimilar' (Webster's New World Dictionary).

1.3.1 Developer Communities

The emergence of a new technology, or even more generally speaking, a new paradigm, presupposes an increasing number of individuals working on a certain subject matter, a certain phenomenon, or some form of artefact. This work can be purely scientific in nature, it can be essentially technological, or it may encompass aspects of both. Whatever the nature of such a project may be, it must, in order to be noticed, gain 'critical mass'. It must transcend the scale and scope of scattered and individual efforts. Something must arise that connects individual efforts and actors. Some authors refer to this as a *'leitbild'*, a 'guiding image' that - by providing a shared goal - functions as a stabiliser for actors from different professions and disciplines.[16] People working towards this 'leitbild' constitute a collective; in this study the collectives are called 'developer communities'.[17]

1.3.2 Developers in Science and Technology

Firstly, developers in science and technology are seen as heterogeneous, resource-dependent and capability-building actors. This notion is in line with the resource-based approach, which assumes heterogeneity and emphasises internal resources as the basis for obtaining competitive advantages.[18] It views organisations as channels for material and immaterial resources. The position

[16] See also Marz, L.; Dierkes, M. (1994). Leitbildprägung und Leitbildgestaltung. In Bechmann, G.; Petermann, T. (eds). Interdisziplinäre Technikforschung: Genese, Folgen, Diskurs. Frankfurt/Main, New York: Campus, 35-72.

[17] In the context of this study, the term 'developer community' is used to denote social entities that unite individuals who advance scientific and/or technological knowledge in a certain direction. These communities can be characterised by similar instrumentation, or their use of a certain subject-matter. Analysts find it increasingly difficult to distinguish between 'science' and 'technology' and, instead, prefer to investigate the dichotomy of 'academe' and 'industry' and efforts to overcome it. In order to avoid the terminological confusion, the term 'developer community' is used.

[18] Wernerfelt, B. (1984). A resource-based view of the firm. Strategic Management Journal, 5, 171-180. See also Rumelt, R.P. (1984). Toward a strategic theory of the firm. In Lamb, R.B.

of an organisation today is the result of decisions and actions made in the past. Different historical developments lead to uniqueness, or heterogeneity, of the resource endowment.

This study assumes that the actors who form developer communities are organisations or individuals that are capable of learning. Moreover, a specific knowledge base is regarded as critical for an organisation to secure the competitive advantage. However, this knowledge base is subject to continuous change and ongoing learning (knowledge accumulation processes).[19] Dynamic capabilities emerge from deliberate and continuous investments in learning and improvement.[20, 21]

1.3.3 Novelty in Science and Technology

There are several ways of denoting novelty. One could use a strictly chronological definition. Then all those events, occurrences, and other incidents that happen within a defined timeframe might be viewed as novel. However, studies that present the innovation process in a sequential pattern remind us that novelty is a context-dependent phenomenon. For instance, market novelty is different from scientific or technological novelty.

A novel technological field can be defined as a field that has essentially evolved within the past 20 years. Mahdi and Pavitt have suggested an analogous concept for 'new science'.[22] They define new science as something

(ed.). Competitive strategic management. Englewood Cliffs, NJ: Prentice Hall.

19 Teece, D.J.; Pisano, G.; Shuen, A. (1997). Dynamic capabilities and strategic management. Strategic Management Journal, 18 (7) 509–534.

20 Hodgson, G.M. (1998). Evolutionary and competence-based theories of the firm. Journal of Economic Studies, 25 (1) 25-56.

21 Teece, D.; Pisano, G. (1994). The dynamic capabilities of the firm. Industrial and Corporate Change, 3 (3).

22 Mahdi, S.; Pavitt, K (1997). Key national factors in the emergence of computational chemistry firms. International Journal of Innovation Management, 1 (4) 355-386.

"that has emerged since 1970 and is characterised by its separation from the parent sciences in literature headings. This separation may take the form of the creation of a new journal, a new keyword or research front in on-line databases, or a new heading in scientific indexes."[23] The authors admit that their definition is not necessarily accurate since developments may have begun several years before the quoted examples, such as the third generation biotechnology and computational chemistry. Also, the definition may not reflect the date of economic impact of the novel field, which could have been felt several years earlier during the incubation phase.[24] Even though the definition presented here does not distinguish between science and technology,[25] it is still useful in describing 'novelty'.

1.3.4 Developer Communities as Complex Systems

Garnsey argues that theories of enterprise and innovation exclude the individuality of the actor,[26] whereas theory dealing with complex systems views individuals and local events as a critical source of diversity and change.[27] This thesis follows Kline, Kash and Rycroft, who suggest that co-evolving technologies and networks are appropriately seen as socio-technical systems that continuously access, create and synthesise tacit and explicit knowledge in the process of innovation.[28] Kline views developer communities

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[23] Mahdi/Pavitt, op.cit., 356.
[24] For instance, the first biotech company, Genentech, was established in 1977, while biotechnology appeared for the first time in 1986 as a 'recognised independent science'.
[25] See Chapter 3.
[26] Garnsey, E. (1998). A theory of the early growth of the firm. Industrial and Corporate Change, 7 (3) 523-556.
[27] See also Allen, P. (1997). Cities and regions as self-organizing systems: models of complexity, Gorden and Breach: London, 2.
[28] Kash, D.E.; Rycroft, R. (1998). Technology policy in the 21st century: how will we adapt to complexity? Science and Public Policy, 25 (3) 70-86. See also Kline, S. (1995). Conceptual foundations for multidisciplinary thinking. Stanford UP. Stanford, CA, 49-97.

as a component of socio-technical systems.[29] He defines socio-technical systems as "complete systems of coupled social and technical parts which humans erect and operate primarily to control our environment and perform tasks we cannot do without such systems."[30] Socio-technical systems are the most complex systems since they include all the other classes of systems and depend on interactions amongst them.[31] A socio-technical system derives its complexity from a multitude of interrelated connections between its elements.

Complexity in turn gives the system its character as unity of a plurality.[32] The system as a unity is complex insofar as it has several elements which it connects through several relations. The number of possible relations between elements grows in geometric progression. However, interconnectivity is drastically limited in reality. Hence, this mathematical law just allows for selectively interconnecting elements. Thus, complex systems are different from simple systems because only in simple systems is it possible to relate each element to another in any possible way at any time. In complex systems, relations between elements are the result of a selection process. Selection leads to *contingent situations.*[33] The purpose of this dissertation is to help identify factors that shape particular situations arising when a novel community unfolds at the interface between science and technology.

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29 Kline also distinguishes four distinct socio-technical systems, namely manufacturing systems, systems of use, systems of distribution, and systems of research and development for creating new or modified socio-technical systems.

30 Kline, op. cit., 62.

31 Ibid.

32 Luhmann, N. (1998). Die Gesellschaft der Gesellschaft. Teilband 1. Frankfurt: Suhrkamp, 135.

33 Situations that could possibly be different.

1.4 Contributions

The objective of this study is to shed some light on the forces that shape communities in an emerging field at the interface between science and technology. An understanding of these underlying factors (and how to measure them) furthers a better comprehension of the innovative process as such, and also helps to explain why certain technologies do not 'take off'. Insights derived from this study provide a basis for an informed review of technology-focused policies in the area of science-based innovation. So, this thesis contributes to research in the field in the following ways:

- First, it suggests a revised interpretation of patent citations as flows of information that point to potential and reciprocal exchange between science and technology. This study challenges the received interpretation of patent citations of the non-patent literature as a measure for the science-dependence of technology. It does so by characterising these patent citations as a mediated link established by a party that is external to the inventive process, i.e. the patent examiner.
- Second, the thesis employs various formats of patent citation analysis to *show that nanotechnology patents contain more patent citations of scientific literature than other technical fields. Yet the data also indicates that science and technology remain autonomous systems*. Instead of a single, boundary-crossing developer community, there are several scientific and technological communities that approach the nano-scale.

- Third, the thesis identifies *the interest in improving techniques of nano-scale measurement and manipulation as the commonality that links the heterogeneous communities in the case of nano-science and technology.* Both patent bibliometric data as well as narrative accounts confirm Rosenberg's conceptualisation of instrument-driven technological development and are also in line with Price's idea of instrumentalities as a chief mediator between science and technology.
- Finally, the thesis points to the relatively persistent path-dependencies which both countries and firms exhibit in the field of nanotechnology. These path-dependencies severely limit managerial approaches. In particular, the strong technological path-dependency in firms appears to determine the network context in which they explore nanotechnology. In other words, the 'social capital' of firms seems to co-evolve with technological or scientific trajectories.

These findings point to the central role of instrumentation and the mediated nature of exchange between nano-science and technology. The thesis therefore concludes that policy measures should be directed towards supporting education and infrastructure in the area, instead of favouring 'direct' venturing approaches.

1.5 Research design

This dissertation addresses essentially two issues: first, the emergence of a novel field at the interface between science and technology and ways to measure this; second, the interplay between scientific and technological aspects. In fact, as will be elaborated later in more detail, a key method for