WHERE SCIENCE MEETS ITS USE –
Exploring the emergence of the practical relevance of scientific knowledge in the regional context

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ABSTRACT

The objective of this doctoral thesis is to facilitate analyses of the role of universities and scientific research in regional development. To this end, the thesis investigates how the practical relevance of scientific knowledge emerges. Instead of adopting the dominating assumption in the literature, namely that scientific knowledge becomes exploitable in university-industry relationships, the thesis approaches the question of practical relevance from three complementary perspectives: that of the regional development process, the innovation process, and the scientific knowledge creation process. The empirical cases chosen to exemplify such processes have their origins in the University of Turku, Finland, and they all relate to efforts to commercialize knowledge that has been created in this university context.

The thesis is a compiled work, consisting of an introductory essay and four research papers, one theoretical and three empirical ones. Whereas the theoretical research paper builds on literature-based conceptual analysis and development, the three empirical studies employ different forms of process analysis. In the theoretical paper, the focus is on the nature of scientific knowledge. In the empirical studies, the focus is on people who use scientific research to accomplish something in practice. These actors are trying to realize their interests while circumstances, resources, and technologies are setting limits to their possibilities to do so. It is assumed that the practical relevance of science forms in such processes.

The thesis makes three main contributions to prior research. First, it confirms that the regional conditions for creating practically relevant scientific knowledge originally emerge through self-organized networks, rather than through top-down governed entrepreneurial university initiatives. An additional finding is that the founding process of the university does not appear to have as strong an effect on later regional development processes as prior research indicates. Second, the thesis demonstrates the uncertain and ambiguous nature of knowledge creation during a radical innovation process and argues that the subsequent management challenges are usually not adequately taken into account in research on regional science-based innovative activity. Third, the thesis presents a novel typology of scientific knowledge, which provides a more clearly defined account of research-based knowledge and knowing than the more generic typologies of knowledge previously employed in this research context. The resulting concepts enable studying the processes in which knowledge is combined into innovations of various degrees of novelty.

KEYWORDS: Scientific knowledge, practical relevance, knowledge types, universities, innovation, regional development, process analysis

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1 INTRODUCTION

1.1 Scientific knowledge creation and economic development?

In the present era of knowledge-based economic development, there are increasing pressures to find ways to have university knowledge creation serve the purpose of economic development through technological innovation. The attempts to do this are often organized on a geographical basis. For example, Finland was the first nation to adopt the framework of a national innovation system as the foundation of its science and technology policy (Miettinen 2002), while also regional efforts to harness the economic value of science through science parks, technology centres and technology transfer agencies abound in Finland as well as elsewhere in the world.

We know fairly well what the eventual societal benefits of scientific research are at a general level and in the long run (Brooks 1994; Salter and Martin 2001). Especially now, when the big challenges posed by climate change, the aging population, the rising energy prices and the general economic downturn are upon us, many solutions are dependent on our ability to turn research knowledge into radically novel solutions. However, our understanding of the nature of the underlying issues is far from complete. This is adeptly illustrated in the below quotes from the evaluation reports of the Finnish national innovation system:

> *As Europe has approached the world technology possibility frontier and is leaving the era of catching up to the U.S. behind, innovation and highly-educated people are becoming crucial drivers of its growth potential. This development has put new demands and pressures upon universities. More and more emphasis is put on ensuring that the capabilities of universities contribute to countries' economic and social objectives* (Veugelers et al. 2012, 240).

> *Innovation policy should mostly be concerned with the coming up with, and employment of, truly novel ideas (new-to-the-world and radical/disruptive innovations) with considerable societal significance.* (Evaluation of the Finnish National Innovation System – Policy Report 2009, 10)

> *Innovation policy remains an art rather than a science. In the context of this evaluation, we largely took the premises for innovation policy for granted, even if we are fully aware that the underlying theories and empirics remain less-than-satisfactory to effectively guide policymaking, which poses a challenge.* (Evaluation of the Finnish National Innovation System – Policy Report 2009, 5)

As innovation policy makers try to base policies on state-of-the-art knowledge, they must take into account that scientific knowledge cannot simply be "transferred" from the academic realm to the economic realm. Innovation research has long since replaced the simple linear conception of innovation (Bush 1945) with more interactive models of innovation (Kline and Rosenberg 1986; Chesbrough 2003). The interactive view of innovation has also been underlying the system approach to innovation at the national (Freeman 1987; Freeman and Lundvall 1988; Lundvall 1992) as well as the regional (Cooke 2001) levels. Current research shows an awareness of the demand and use aspects of innovation as well as the process and service forms of innovation that complement the traditional understanding of innovation as a technological phenomenon only. It is problematic, however, that while the overall understanding of innovation has become refined by having these new elements encompassed into it, the science side of innovation has been somewhat neglected theoretically (Balconi et al. 2010). For instance, the innovation system perspective provides schematic rather than detailed accounts of the processes through which universities and scientific research feed into the technological development in the national or the regional context. Similarly, the accounts of knowledge-based regional development are characterized by a lack of attention to the dynamic aspects of scientific knowledge. The discussion tends to focus on the need to increase the interaction between academic and industrial parties, but the related processes, where scientific knowledge embraces or is embraced by questions related to its use, are rarely addressed. The present thesis seeks to contribute to the research on knowledge-based regional economic development by focusing on such processes.

1.2 The practical relevance of scientific knowledge from three perspectives

> *…it is necessary—already at this point—to engage in historic and long-term investigations in the Schumpeterian sense of de-*

> *velopment that describes the non-equilibrium processes that transform the economy from within, through the formation and diffusion of technological knowledge, exemplified by the continual introduction of novel products and processes into the market place, in order to provide a comprehensive analysis of technology trajectories (Schumpeter 1934, 1942). Of course, such a unique evolutionary perspective includes aspects that reach well beyond narrow territorial perspectives or deterministic spatial considerations as the intellectual journey continues.* (Kogler et al. 2011, 276)

The above closing sentences from the book *Beyond territory* (Kogler et al. 2011) convey an approach that also underlies the present thesis work. The economy-transforming properties of innovations as well as the formation of the underlying knowledge have continued to arouse the curiosity of researchers since the times of Joseph Schumpeter. It is obvious that the related phenomena transcend geographical scales and locations. Yet the same phenomena are crucial for the economic development of almost any location. This is why research on regional development must find ways to grasp and analyze knowledge creation, technological innovation and the nexus between the two in a way that does not superimpose a certain spatial scale on them, yet understands that such processes always unfold in specific geographical contexts. In the present thesis, this double act is attempted by conducting the analysis as close to the knowledge-creating and innovating actors as possible, and by connecting the findings to discussions that are more explicitly regional.

This topic of the thesis is the ways in which natural and medical sciences become useful and exploitable in technological innovation. More specifically, the focus is on the emergence of the practical relevance of scientific knowledge, i.e. the various processes through which scientific knowledge becomes regarded as relevant and valuable for achieving practical aims. On the one hand, scientific knowledge can be considered relevant if it can be used to achieve some new technical functionality. On the other hand, knowledge becomes relevant if this new functionality is considered economically valuable by those with the resources to invest in the technology. Such processes occur at the very early stages of innovation, or even before the actual innovation processes are initiated.

Generally, the research on regional innovation and knowledge-based regional development entertains the view that the nexus of scientific knowledge and innovation is formed in the interaction between universities and industrial parties, as the former aim to produce knowledge and the latter aim to commercialize innovations. This generic view has been further conceptualized by

Cooke (2004), who sees the role of universities and other research organizations as being the production of exploration knowledge (research) and that of firms as being its transformation into products, processes and services that have market value, by using exploitation knowledge (commercialization) (Cooke 2004). The present thesis accepts the view that the institutional context of knowledge creation is different in universities and firms, and that the exploration / research and exploitation / commercialization activities reflect these differences. However, the present thesis takes a step back from the presupposition that to understand how scientific knowledge becomes useful for the economy it is enough to study only university-industry interaction or the organizational forms and intermediaries that link the activities of these two parties. Rather, to complement this view, this thesis studies the emergence of the practical relevance of scientific knowledge from three other perspectives that are inspired by research in the field of Science and Technology Studies (STS). The inspiration gained from STS is first and foremost epistemological and methodological: in this field, it is rather common to focus closely on the actors that are involved in the development of science and technology. The three perspectives employed in the present thesis have this kind of underpinning.

The first of these perspectives involves looking at the topic in the regional context. If the institutional thickness (Amin and Thrift 1994) of the region is sufficient, its different stakeholders may attempt to facilitate science-based innovation activities. In this regional context, the practical relevance of scientific knowledge is sought by embracing, for example, the idea of the entrepreneurial university (Etzkowitz et al. 2000) and the third mission of the university. In the regional context, practical relevance does not concern particular "pieces" of knowledge; it concerns more generally the role of public research in the regional economy. The present thesis, as well as some recent studies (Benneworth et al. 2009; Hommen et al. 2006), find the founding of a science park a particularly illuminating example of a process where regional actors display diverse and changing expectations toward scientific knowledge creation and its relation to its environment.

The second perspective from which the creation of the practical relevance of scientific knowledge is studied is that of the innovation process. In this context, scientific knowledge is understood as useful and practically relevant if it enables or supports the commercialization of an innovation. The related research concerning the regional economic impact of university research takes it somewhat for granted that science-based inventions are of economic relevance. The present thesis, on the other hand, seeks to uncover the complexities involved by opening up the managerial challenges that the actors must struggle with as they seek to commercialize a potentially discontinuous (Colarelli O'Connor 1998; Garcia and Calantone 2002) science-based invention. The analysis reveals that the early phases of the radical innovation process entail continuous re-interpretation and elaboration of the meaning, significance and relevance of the core insights. It is not even evident what should be regarded as "knowledge" in this context, as the research findings and claims may remain contested for extensive periods of time. To simplify such an ambiguous process under the terms "exploitation" and "commercialization" of knowledge would hide many of the challenges related to the creation of new science-based business.

The third perspective focuses on scientific research activity. In this context, scientific knowledge is relevant in practice if it can be used to enable or support the accomplishing of some task or function in a novel way. The relevant body of research directly concerns the types of knowledge involved in innovation (Asheim and Gertler 2005; Lundvall and Johnson 1994). These approaches claim that the understanding of the role of knowledge in innovation requires more elaborate conceptualizations than the prevailing dichotomy between tacit and codified forms of knowledge (Polanyi 1966). They do not really address *how,* precisely, scientific knowledge becomes relevant in practice. To understand this, it is again necessary to take a closer focus on the actors, as well as on the knowledge creation processes they are involved in.

All in all, the present thesis seeks to provide novel concepts as well as new empirical knowledge for understanding how scientific knowledge comes to affect technological development. The underlying purpose is *not* to analyse the entire process through which science makes its eventual, "visible" impact on the economic development of the region. The paths from science to regional development are too complex to be properly analysed in a single thesis. This is not least because the economic activities that rely on university research may become realized quite far from the region where the knowledge was originally created (Power and Malmberg 2008), especially in cases of so-called analytic knowledge creation (Moodysson et al. 2008).

The purpose of the present thesis is to open up some of the complexities involved in the earliest phases of knowledge and technology development that *may* at some point contribute to regional economic development, as well. The empirical insights gained are used to comment on the findings of the prior research on regional development from a new angle. Additionally, the research provides new analytical concepts for conducting further studies of the interface of science and innovation in the regional context.

In light of the above discussion, *in order to facilitate analyses of the role of universities and scientific research in regional development*, the present thesis poses the following research question:

How does the practical relevance of scientific knowledge emerge?

The creation of the practical relevance of scientific knowledge is approached from the above-mentioned three perspectives in four interrelated pieces of research concerning the innovation development and scientific research conducted in the University of Turku, Finland.

1.3 Structure of the thesis

This thesis is divided into the present introductory essay, the two published articles and the two article manuscripts (submitted to scientific journals). The introductory part is organized as follows. The second section looks at the literature that discusses the role of scientific research in knowledge-based regional and/or economic development. The section identifies a set of knowledge gaps in the earlier research that relates to the three perspectives outlined above. The identification of those knowledge gaps helps to formulate a set of more specific sub-questions to the main research question. The third section presents the data and methods utilized in the individual studies. The fourth section presents the results. The fifth section presents the conclusions and suggests avenues for further research.

Table 1 lists the three perspectives utilized in the present thesis, the bodies of research where knowledge gaps are identified, and the individual articles (A1 and A2) and article manuscripts (AM1 and AM2). The articles and manuscripts are listed in the order that they have been written. They reflect the author’s increasing interest towards the nature and role of knowledge in innovation.

Table 1 The three different perspectives on the topic of the thesis.

Gaps and contributions	***Regional development***	***Innovation development***	***Scientific knowledge development***	
Bodies of research where knowledge gaps are identified	Research on entrepreneurial universities & Triple Helix	Academic entrepreneurship & research on regional aspects of innovation	Knowledge-based economic regional development: learning economy & differentiated knowledge bases approaches	
Article/ Manuscript number	A1	A2	AM1	AM2
Specific purpose of the analysis	To explain the emergence of a science park facility	To analyze the challenges that a high degree of novelty presents to science-based innovation development	To conceptualize scientific knowledge types from the perspective of technological innovation	To study how knowledge created in university research contributes to the innovation process
Key contribution	Demonstrating the role of local self-organizing networks in regional science-based development	Showing how various discontinuities may hinder the development of science-based innovations	Developing a typology of scientific knowledge	Showing how practical relevance is gradually built into research.

A1 introduces the thematic and geographical background of the thesis: the aspirations to support regional economic development with science-based innovation in Turku. In this regional context, the practical relevance of scientific knowledge is reflected in the ways that the different stakeholders understand the university's role and mission. A1 shows how different stakeholders are able to agree on the necessity to join forces in order to support local science-technology interaction through the construction of a biotechnology science park facility.

A2 goes into the level of innovation development and management, where forming relevant knowledge requires much more than the bringing together of scientific research and industrial interests. A2 reports a case study of a radical innovation project unfolding in the context of Turku Science Park and investigates the challenges that the high degree of innovativeness introduces to the project.

In AM1 and AM2, the focus of analysis is moved from the innovation process to the actual scientific research. Here, the interest is on the processes that create the science base of radical innovations. The function of AM1 in this thesis is to develop a conceptual toolset that enables analyzing the topic empirically. AM2 operationalizes the approach to study how practical considerations emerge in scientific research. The study concerns three research trajectories that have unfolded in the Medical Faculty of the University of Turku and resulted in radical innovations in three different decades.

From amongst the findings of this research, three key contributions emerge. The first of these involves showing the importance of local, self-organized networks and the quality of the regional planning process for the ability to utilize scientific knowledge as part of regional economic development. The second key contribution lays in showing how various discontinuities potentially hinder the emergence of the practical relevance of scientific knowledge that might give rise to innovations involving a high degree of novelty. The third key contribution involves the conceptualization of the different types of scientific knowledge, which in turn enables studying the processes in which knowledge is combined into innovations of various degrees of novelty.

2 THREE PERSPECTIVES INTO SCIENTIFIC KNOWLEDGE CREATION IN THE REGIONAL CONTEXT

2.1 The impact of universities

This section takes a look at research addressing the broader role of universities in the economic development of the regions in order to demonstrate that there is a research gap in regard to understanding the processes through which the practical relevance of scientific knowledge becomes an issue between the regional actors. The discussion is limited to the regional role of academic research rather than that of education.

Much of the research on the contribution of university science to the regional economy focuses on characterizing the spatial extent or the nature of the spatial impact of university knowledge creation. A classical way to approach this is to study the spillovers of university knowledge, in which context it is found that university knowledge both benefits and attracts firms in the locality (Jaffe 1989; Jaffe et al. 1993). Some studies argue that academic spin-offs play an important role in regional economies, as they commercialize research-based knowledge (Audretsch et al. 2005; Benneworth and Charles 2005; Bercovitz and Feldman 2006), while other studies are sceptical of the ability of university spin-off firms and related support policies to impact regional development in any significant sense (Koschatzky and Hemer 2009; Miner et al. 2001; Miner et al. 2012). Even though the significance of the spin-off phenomenon for regional development has been debated, it is fairly well established that the local impact of university research is particularly strong in the dynamics related to firm formation (Feldman and Kogler 2010).

To reveal a broader set of societal influences of university research, some researchers look at the spatial dimension of the activities of individual “star scientists”. For example, Zucker and Darby (1996; 2002) introduced this concept and found that “star scientists” greatly affected the emergence of a local biotechnology industry. Schiller and Diez (2010) found that German star scientists do achieve excellence in both academic and industrial spheres, but are not particularly locally embedded, except for academic research collaboration. The issue of the regional role of the university is further complicated by the existence of multiple indirect influences that are difficult to pinpoint and measure; they are not exclusive to certain localities or certain parts of the innovation process and they play out differently in different locations (Brezniz and Feldman 2012; Goldstein 2009; Jacobsson and Vico 2012).

These different takes on the role of academic knowledge in local and regional economies have in common that they seek to explain *where* academic knowledge creation impacts—or does not impact—economic development. In a way, such research maps the different aspects of the spatial "footprint" of university research. It leaves a research gap in that it does not explain *why* and *how* academic knowledge creation comes to affect the economic and technological development in some localities and not in others (cf. Howells 2002). Most previous studies are "static in nature and only provide a snapshot, or post-developmental retrospective view, of the dynamic processes that lead to innovation and technological change in the first place" (Kogler et al. 2011, 276). Power and Malmberg (2008) argue that processes in science, innovation and value creation strive for excellence by using very different criteria, which are globally rather than regionally defined. In the light of these underlying dynamics, Power and Malmberg (ibid.) argue, there is no reason to expect that in a specific region links would necessarily, let alone systematically, form between the scientific research in the universities, the capacity for innovation, and the processes of value-creation. However, if this is true, then it is even more important for the research on regional innovation and regional knowledge-based development to understand how and why linkages between these different processes sometimes do form, and in other instances fail to do so.

In order to explain the formation of linkages between research and the capacity of innovation, it is necessary to study the processes in which academic research in certain places embraces, or refuses to embrace, the use of knowledge for innovation. Feldman and Desrochers (2004) have provided this kind of insight. They illuminate how there emerged a culture around Johns Hopkins University in which scientific research came *not* to contribute to the regional industrial development. Their analysis shows how attitudes concerning the practical relevance of research were embedded into the culture of the university since its founding. The analysis also provides evidence of such a culture forming simultaneously at the levels of research and university governance.

Etzkowitz and Klofsten (2005), promoters of the so-called Triple Helix framework, provide an explanation for development that leads to intensified science-industry interaction and related knowledge-based regional economic development. They claim that the traditional "linear" knowledge transfer through the publication of research results and the recruitment of graduates is not enough for knowledge-based economic development to occur. Etzkowitz and Klofsten (ibid.) develop a view on the four stages that are required for the entrepreneurial university to emerge and to create an “innovating region” around it. First, the local university must become able to set its own strategic direction. Second, there must be an orientation for seeking out both the practical and the theoretical implications of the knowledge produced, and associated organizations to help in the technology transfer and firm formation must also be founded. Third, university students must receive entrepreneurial training. Finally, centres to encourage the formation of knowledge with both practical and theoretical relevance have to be established. As a result, there emerges an “’Assisted Linear Model’ comprising a variety of interlocking organizational mechanism (sic) such as research centres, technology transfer offices and incubators that move research with long-term commercial potential into use” (ibid., 245). In this “assisted” model, the legitimacy of using scientific knowledge to solve practical problems is first established in the regional level and among those capable of steering the university. The search for the practical relevance of knowledge is presented as an attitude that can and must be reflected in the organizational structure of the local knowledge system, as well as taught to students as part of their education. Only then can actual knowledge with both practical and theoretical relevance emerge and be transferred to the industry.

Hommen et al. (2006) have strongly criticized the emphasis on university, industry and governance elites that prevails in this Triple Helix explanation of knowledge-based regional development. They show that when studying the preceding and very early phases of forming a science park, a very different story with a much more diverse set of initiators may emerge. According to the analysis of Hommen et al. (ibid.), the university played an important but rather passive role whereas the loose and temporary development coalitions that responded to momentary crises drove the entrepreneurial development forward. Based on their study, Hommen et al. (ibid., 1357) call for research that pays more attention to the early phases of science park development and takes a more interactive and broad view than that advocated by the Triple Helix approach.

The studies above make clear that it is important that the search for the practical relevance of knowledge is established in multiple contexts (regional, educational, corporate, and research contexts). However, these results contradict each other in regard to the role of the university, leaving it unclear whether a strong entrepreneurial vision of the local university is necessary for regional development to take place. From the perspective of regions where universities have not become entrepreneurial and seem disinclined to do so, it would be important to know how a willingness to pursue the practical relevance of knowledge may come about.

The process of founding a biotechnology science park in Turku, the historical capital of Finland, illuminates this issue in an interesting way. Finland provides a suitable context for such a study, as in the 1960s and 1970s, the Ministry of Education, which was responsible for the funding of universities, was strongly in favour of scientific research keeping its distance from industrial interests (Immonen 1995). Yet, by the 1990s, university-industry interaction had become the word of the day, and technology centres and science parks suddenly sprung up all over the country. To explain how such a development was possible in the case of the traditional universities of Turku, this thesis illuminates the creation of the practical relevance of scientific knowledge in the regional context by posing the following sub-question:

1. *How was the biotechnology science park created in Turku?*

This question is especially addressed in the first separate study (A1) of the present thesis.

2.2 The development of science-based innovations

Science-based innovations are more frequently radical than innovations of a less research-based origin (Tödtling et al. 2009). However, despite the perceived importance of universities and university research for innovation, the degree of innovativeness is surprisingly rarely given a central position in the analyses of regional innovation. For instance, Oinas (1999) finds that little attention is paid to the need for relations with local and more distant environments along the incremental-radical dimension of innovation development. Subsequently, Oinas and Malecki (2002) classify regions into adopters, adapters and genuine innovators. They link this typology with Storper and Salais' (1997; see also Storper 2011) "worlds of production". Oinas and Malecki (2002, 115) argue that the "world of intellectual resources", where scientific methods are used in product development, is at the core of the regions that are genuine innovators, co-existing with the "interpersonal world" which is the locus of the leading edge of innovation. The co-existence and interaction between the different worlds implies that the potential lack of regional connections, as presented by Power and Malmberg (2008, see section 2.1), has been solved in genuine innovator regions. The question is, of course, how regions become genuine innovators.

Later, a similar kind of differentiation between the incremental and radical forms of innovation has been given significant attention in the differentiated knowledge bases approach (Asheim and Coenen 2005; Asheim and Gertler

2005). In this context, the firms' access to research has been presented as increasing the degree of innovativeness of their products. This view is in line with the empirical findings of Tödtling et al. (2009). Innovating that relies on the "analytical knowledge base" of science—which is prevalent in innovations that tend to be more radical—are found to be less dependent on the proximity between the knowledge source and product development than the innovating based on engineering knowledge (Moodysson et al. 2008). The argument underlying this view is that scientific knowledge is regarded as codified and transferable (Asheim and Gertler 2005) and therefore relatively easy to communicate over distance.

There is a problem, however, in associating science-based radical innovations with the codified and transferable nature of related knowledge. This may lead to over-estimating the ease of communication in the cases of radical innovation development, and to the overlooking of the communication problems that otherwise may be inherent to radical innovations. This problem becomes evident when considering the meaning of radicality in more depth.

According to Garcia and Calantone (2002), who offer one of the most systematic classifications of the degree of innovativeness of innovations, radical innovations involve both technology and market "discontinuity" (Colarelli O'Connor 1998; Tushman and Anderson 1986). Innovations that involve either technological or market discontinuity, but not both, can be considered "really new" innovations (Garcia and Calantone 2002). Further, newness may be either industry-wide or just newness in the context of a firm (ibid.). From the perspective of the present thesis, it is significant that science-based innovations typically involve technological novelty, which means that they are at least "really new" and possibly also "radical" in the industrial level. The consequences of the industry-level newness and related market discontinuity aspect are not usually considered in the research concerning science-based innovation activities and respective learning and regional development. Specifically, the research does not discuss whether the development processes of radical innovations that involve both market and technology discontinuity are meeting different challenges and benefiting from a different set of resources and conditions compared to the development processes of innovations that are only technologically novel but do not necessitate the creation of an entirely new kind of market.[1]

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1 A similar lack of attention to the potential problems of gaining resources for science-based innovation development is visible also in the research that reveals the motivations of academic entrepreneurs without addressing the associated challenges. For example, Feldman (2000) shows that, in the U.S., even the universities that are most strongly oriented towards basic science have recently had to embrace entrepreneurial templates to allow the best scientists to benefit most from their research. In this context, the principal reason for creating academic spin-off companies are related to the necessity of researchers to gain funding and career opportunities when research groups become too large to

The only field of study that touches upon the problems of entirely new market-creation from the spatial viewpoint is the geographically oriented research on so called sustainability transitions (Coenen et al. 2012). Even here, the connection to the present theme is not direct, as the theoretical emphasis is on the sustainability-enhancing potential of the radical innovations rather than on their possible basis in scientific research. But transition research is particularly clear on the potential difficulty of market-creation for those innovations that do not follow established technological trajectories (Dosi 1982). The question motivating transition studies is how the existing socio-technical systems, such as waste treatment, energy production or transport, could be replaced with more sustainable solutions, when the different dimensions of the existing system (technology and products, science, policy, socio-cultural, users, markets and distribution networks) are strongly interlinked and form a "regime" which new entrants can hardly break into (Geels 2004; 2005). The related concept of regime (see the "prism" in the centre of Figure 1) is a useful reminder that the market is not necessarily readily welcoming various kinds of radical, possibly science-based solutions. Rather, it forces the aspiring entrepreneurs to struggle with considerable challenges in developing and commercializing innovations that do not fit with the entrenched regime.

sustain themselves by public funding (Feldman 2000; see also D'Este and Perkmann 2011; Franzoni and Lissoni 2009; Hayter 2011). What these studies do not address, however, is that such entrepreneurs are immediately faced with the problem of demonstrating the practical relevance of scientific knowledge to those holding the capital and other resources. This challenge is likely to be accentuated in cases of discontinuous innovations and in regions where venture capital is not abundantly available.

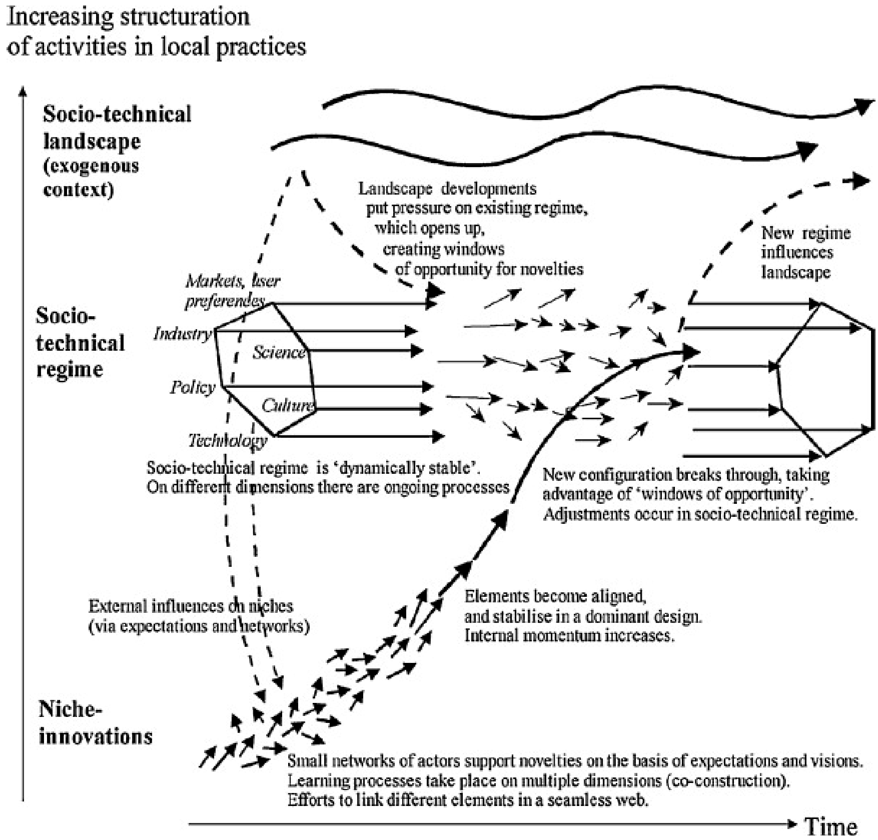

Figure 1 Multi-levels perspective on system innovations (Geels and Schot 2007, 401).

In transition research, the idea of the development of individual radical innovations in particular "niches" is conceptually important, but the cases studied usually concern entire system transitions (Geels and Kemp 2007) rather than the development of individual radical innovation projects in the niche context of a larger transition process. Geographically sensitive analysis of sustainability transitions is only emerging (Coenen et al. 2012; Markard et al. 2012; Raven et al. 2012; Truffer and Coenen 2012). In this branch of research, however, attention is beginning to be paid to individual local solutions in meeting the challenges of radical innovation development. Coenen et al. (2012) argue that the contribution that geographers are making can be summarized in three axioms for the study of transitions: "(1) [global and local] scales are actively constructed through socio-spatial struggles by actors seeking to achieve their ends (2) following those relationships and struggles allows interpretation of the ways within which small niche experiments become influential in wider regimes (3), and that the way different scales interrelate in particular circumstances provides a means of understanding and comparing case studies" (ibid., 976).

Not all science-based innovations are radical, nor are all science-based radical innovations parts of broader sustainability transitions. Given that the existing regional innovation studies tend to regard science-based innovations as potentially radical, without recognizing the possibly challenging nature of radical innovation development, it is proposed here that the multi-level perspective on socio-technical regime change illuminates the challenges related to establishing the practical relevance of science-based radical innovations. Moreover, the geographical branch of transition studies with its three axioms might offer a theoretically particularly inspiring approach for analyzing environments that would support the development of radical innovations in specific locations.

Nevertheless, the jump from spatially sensitive transition analysis to spatially sensitive science-based innovation environment analysis remains difficult as long as there is a very limited understanding of the ways in which the encounters between the science-based innovation project and the regime actually take place and what the respective management challenges are that the innovators must meet and resolve to keep the project moving. To study what kind of struggles are involved, the present thesis therefore analyzes the development of the on-going, science-based innovation project that at the time of study was unfolding in the context of Turku Science Park. The project aimed at introducing an innovation that can be considered radical or discontinuous in the context of the diagnostic industry. The second sub-question of the thesis is hence posed as follows:

2. *What are the challenges of demonstrating the practical relevance of an ongoing, potentially radical innovation project?*

This question is especially addressed in the second separate study (A2) of the present thesis.

2.3 The use of scientific knowledge in innovation

2.3.1 Questioning the new Mode of knowledge production

According to Gibbons et al. (1994), the organization of knowledge production is increasingly moving from a disciplinary-based Mode 1 toward transdisciplinary and socially distributed knowledge production in the context of application, the so-called Mode 2. Given that *The new production of knowledge* (Gibbons et al. 1994) was published nearly twenty years ago, it is striking how well some of the claims presented seem to match the developments surrounding today's universities: the importance of transdisciplinary fields such as materials science, the opportunities to participate in socially distributed knowledge production through the use of various digital applications, and the demands by the funders of science for problem-based research are all trends that seem to be only strengthening.

However, despite its apparent insightfulness when describing the on-going changes in knowledge production, it is difficult to decide what to eventually make of the collection of claims related to the Mode 1 and Mode 2 argument. For instance, the claim that a new mode of knowledge production is emerging (Gibbons et al. 1994) has been criticized for not adequately taking into account the history of science (Shinn 2002). Rather, the more basic and more application-oriented modes of knowledge production can be said to have existed alongside each other for a long time, with some more emphasis towards the features of Mode 2 in the recent decades (Martin and Etzkowitz 2000). In other words, transdisciplinary research has always been with us, even if it currently is more in fashion than in some other decade

Even disregarding the disputed "newness" of Mode 2, it remains difficult to grasp how the argument would inform further research. From the perspective of the present thesis, the most problematic aspect of the Mode 2 argument is that it lacks empirical evidence, a methodological programme, a theoretical foundation and conceptual clarity, as argued by Shinn (2000). The book (Gibbons et al. 1994) indeed makes a strong case that the practical relevance of scientific research is increasingly at the core of great many interests, but it offers little help for the empirical investigations into how precisely the practical relevance of knowledge emerges. The situation does not significantly improve in this regard in the second core book presenting the Mode 2 approach, *Rethinking science* (Nowotny et al. 2001). For the purposes of the present thesis, conceptually less ambiguous branches of research must therefore form the basis of investigation.

2.3.2 Beyond the tacit/codified distinction

The fundamental level at which scientific knowledge may become practically relevant is where it first becomes associated with a use. From the regional development point of view, understanding is needed on the kinds of contexts where specific "pieces" or "lines" of scientific knowledge first become considered useful for innovation and economic development. This is, however, incompletely understood in the research, partly due to the lack of attention given to science-related themes in the regional research on knowledge-based or learning-based regional development. Throughout the 1990s, the discussion on the role of knowledge in regional development tended to emphasize the interactive learning which takes place between different regional actors. The commonly made distinction between tacit and codified forms of knowledge (Camagni 1991; Capello 1999; Cooke and Morgan 1998; Gertler 1995; Keeble et al. 1999; MacKinnon et al. 2002; Morgan 1997; Storper 1997) gave rise to the argument that the easier it is to access codified knowledge, the more important tacit knowledge and the related proximity between interacting parties become (Maskell and Malmberg 1999). Scientific knowledge was mostly assumed to be codified and thus it received less attention in this research than did tacit knowledge that was associated especially with practical problem-solving in the context of use. The emphasis on the use of knowledge may have been further amplified with the tendency of innovation-related research throughout the social sciences to avoid the association with the “linear model of innovation”, in which the importance of scientific knowledge in innovation had been over-emphasized (Balconi et al. 2010).

While it has been noted that also scientific knowledge and its transfer involve tacit elements (Gertler 2003; Howells 2002), the tacit/codified distinction alone has not brought research much closer to understanding how scientific knowledge can contribute to innovation and thus to regional development.

Recently, research has explicitly assessed the role of scientific knowledge in innovation and economic development. This has taken place in at least three strands of research, one represented by Bengt-Åke Lundvall and his colleagues, one by Björn Asheim and his colleagues, and one by Phil Cooke and others employing the idea of Regional Innovation Systems (RIS). In the following sub-sections, it is discussed what these different approaches have to say about the formation of usefulness and practical relevance of scientific knowledge.

2.3.3 Knowledge types

When launching the concept of the “learning economy”, Lundvall and Johnson (1994) introduced the idea of innovation hinging on the ability to combine different kinds of economic knowledge. This, and the subsequent research by Lundvall and his colleagues, has not been explicitly geographical, but it has been influential among researchers of regional development.

The understanding concerning the practical relevance of scientific knowledge is, naturally, dependent on how knowledge, and scientific knowledge in particular, is defined. Lundvall and Johnson (1994) differentiate between “know-what”, “know-why”, “know-how”, and “know-who” types of knowledge. When the typology was created, there was no particular emphasis on scientific knowledge yet. Lundvall (1998) proposes that the typology is useful for differentiating between “national styles of innovation”, whereas Johnson et al. (2002) use it to clarify the nature of tacit knowledge. Johnson et al. (ibid.) argue that the four different types of knowledge are codifiable to a different degree, and that full codification of know-how, especially, is neither achievable nor desirable. The study by Johnson et al. (ibid.) associates scientific knowledge with know-why, which is “knowledge about principles and laws of motion in nature, in the human mind and in society” (ibid., 250). Their study presents this knowledge as usually being codified, although in an incomplete manner, as science-based activities build on the specific scientist’s personal know-how, as well.

This line of research has focused directly on the relation between scientific knowledge and innovation in the recent work that builds on the above-mentioned four types of knowledge (Jensen et al. 2007; Lundvall and Lorenz 2007). In this work, the knowledge typology has been used to distinguish between the two modes of learning and innovation in firms, one of which bases the innovation activities on scientific knowledge, and the other with its basis on experience-based knowledge. The first mode is named the Science, Technology and Innovation (STI) mode, and the latter is the Doing, Using and Interacting (DUI) mode of innovation. Firms following the STI mode rely on and further develop know-why and know-what types of knowledge, while firms following the DUI mode use and develop know-how and know-who types of knowledge. This seems to mean that only firms following the STI mode are involved in making scientific knowledge practically relevant through innovation.

Jensen et al. (2007) argue that the distinguishing feature of the STI mode is that despite the tacit elements involved in R&D, the STI mode is strongly dependent on knowledge codification. This is because tasks need to be solved in a modularized manner, which requires documentation in order for the knowledge to be shareable among the team, within the firm, and possibly with external scientists as well. For the firms following the DUI mode, the most important knowledge is learned through experience and it often remains tacit.

Jensen at al. (2007) use the conceptual distinction between the STI and DUI modes of innovation to study the sources of innovativeness of firms. They argue that firms that combine the STI mode with the DUI mode excel in product innovation. Lundvall and Lorenz (2007) further argue that such combining of different modes of innovation is becoming ever more prevalent, to the extent that Pavitt’s (1984) sectoral taxonomy involving science-based producers as a separate category is not valid anymore. R&D functions need to be increasingly connected to functions implementing, marketing, and using the outcomes of the creative process. Non-science-based sectors are also increasingly drawing on science in their product development. Lorenz and Lundvall (2007) argue that while there are sectoral differences, the overall tendency is that the "creativity phase" and the "innovation phase" (the production of ideas and the application of ideas) are becoming parallel, or indeed fusing into one process.

This argument seems to imply that academic research is increasingly conducted in relation to industrial development. This is not necessarily the case, however. Even though Jensen et al. (2007) in the theoretical part of their study claim that scientific knowledge is of the know-why kind, mostly codified, and pertains to artefacts and technologies (ibid., 682-3), the indicators used in the empirical part do not reveal whether these assumptions actually hold. According to the empirical indicators employed, the STI mode simply means that firms spend on R&D, interact with external scientists, and employ scientifically trained personnel (ibid., 687, 691). These features offer little illumination on the kind of scientific knowledge that enters the company with the science-trained employees or through interaction with external scientists. Hence, it is impossible to say how scientific knowledge is associated with a potential use and whether this happens before or after the knowledge enters the company, for example. It would be essential to better define the nature of the scientific knowledge that moves between academic knowledge creation and innovation development, in order to study more in depth how and why companies in practice benefit from increasing the share of scientific input in their product development.

2.3.4 Knowledge types or knowledge bases?

Among the research that focuses more explicitly on the regional aspects of knowledge-based economic development, the differentiated knowledge bases approach (Asheim and Gertler 2005; Asheim and Mariussen 2003; see also Coenen et al. 2004) is the one that most directly discusses the role of scientific knowledge in innovation. The approach refines the simple tacit/codified conceptualization of knowledge by arguing that industries utilize tacit and codified knowledge to a different degree depending on the nature of their key knowledge base (Asheim 2012; Asheim et al. 2011)[2]. Three broad knowledge

2 This idea of three differentiated knowledge bases has been used to explain and explore the sensitivity to distance of the knowledge creation activities in different industries. The underlining basic argument is that the more the industry relies on tacit knowledge, the more sensitive the respective innovation processes are to the distance to external sources of knowledge. Analyzing knowledge creation with respect to "buzz" and face-to-face contacts has further shown that participating in the local

bases have been defined: analytic, synthetic and symbolic. The core features of each knowledge base are outlined in Table 2 below. The relation to Lundvall and Johnson's (1994) knowledge typology is visible in the second row of the table, where each knowledge base is associated with a specific type of knowledge.

Table 2 Differentiated knowledge bases: A typology (Asheim 2012, 997).

Analytical (science based)	***Synthetic (engineering based)***	***Symbolic (arts based)***
Developing new knowledge about natural systems by applying scientific laws; know-why	Applying or combining existing knowledge in new ways; know-how	Creating meaning, desire, aesthetic qualities, affect, intangibles, symbols, images; know-who
Scientific knowledge, models, deductive	Problem-solving, custom production, inductive	Creative process
Collaboration within and between research units	Interactive learning with customers and suppliers	Experimentation in studios and project teams
Strong codified knowledge content, highly abstract, universal	Partially codified knowledge, strong tacit component, more context specific	Importance of interpretation, creativity, cultural knowledge, sign values; implies strong context specificity
Meaning relatively constant between places	Meaning varies substantially between places	Meaning highly variable between place, class and gender
Drug development	Mechanical engineering	Cultural production, design, brands

Industries drawing on the analytical knowledge base are presented as directly utilizing scientific knowledge (know-why) in their innovation activities. The resulting innovations tend to be of a radical rather than an incremental nature. Biotechnology and nanotechnology are referred to as examples—apparently the argument is that the industries that utilize these science-based techniques and technologies belong to the analytic knowledge base. Analytic knowledge in these industries is presented as typically being codified to a large degree. This is argued to be due to the importance of reviewing scientific publications for existing relevant knowledge, the use of scientific principles

"buzz" is an important source of knowledge (rather than mere information) for innovation in the industries relying on the symbolic knowledge base. In contrast, innovation in industries relying on a synthetic knowledge base benefits more from specific face-to-face contacts in vertical user-producer relations. Innovation in industries relying on an analytic knowledge base, in turn, benefits from horizontal face-to-face relations between the researchers producing scientific knowledge. However, the role of these informal connections should not be over-emphasized, since the main body of important knowledge of the analytic industries is nevertheless codified and can be conveyed and sourced over distance.

and methods as well as formal organization to create new knowledge, and the need to document the created new knowledge in reports, files and patent descriptions. (Asheim et al. 2007; Asheim et al. 2011)

In the synthetic knowledge base, the role of scientific knowledge is argued to be limited and the key knowledge is rather of the know-how kind. The resulting innovations tend to be incremental. The problems solved in the innovation process typically relate to specific customer problems. Companies may occasionally do R&D or interact with universities, but mainly in the context of concrete knowledge application. Examples given of industries with a synthetic knowledge base are plant engineering, specialized advanced industrial machinery and production systems, and shipbuilding. The most important knowledge in these industries is argued to be tacit, gained through the experience of doing, using and interacting, even if some codification of the engineering solutions does occur (Asheim et al. 2007; Asheim et al. 2011).

In the cultural industries, where innovation relies on the symbolic knowledge base, innovation activities are presented as being unrelated to the scientific knowledge creation. Rather, the ability to innovate with aesthetic symbols, images, (de)signs, artefacts, sounds, and narratives is based on the tacit knowledge that accumulates through artistic experience and in close contact with the everyday culture of various social groupings. Knowledge of the “know-who” kind is argued to be particularly important for this context (Asheim et al. 2007; Asheim et al. 2011).[3]

The knowledge bases approach was not originally developed for fine-grained analysis of knowledge creation processes, but for characterizing generic types of innovation processes in firms, arguing that these tend to be of different nature in different sectors. The generic nature of the approach has, however, given rise to criticisms that are relevant in regard to the research question of the present thesis. Lundvall and Lorenz (2007), as well as Manniche (2012), have noted that it is problematic to characterize entire industries or entire firms as relying on a single knowledge base. Manniche (ibid.) argues that the knowledge bases approach is, in fact, most suitable for recognizing types of particular “knowledge interactions” within and between organizations, because at a higher level these organizations and networks actually combine multiple knowledge bases. Also Asheim et al. (2011, 898; see also Asheim 2007, 226) note that the knowledge bases are ideal types, while in practice firms utilize more than one type of knowledge creation activity (see Moodysson et al. 2008).

3 As the symbolic knowledge base is not characterized as relating to technological innovation, it is not discussed further in this section.

But even if the differentiated knowledge bases approach was decoupled from the industrial level of analysis and, instead, applied at the level of particular interactions during the innovation process, a methodological problem remains, pertaining to the correct categorization of various science-related "knowledge interactions". While the different knowledge bases approach makes intuitive sense and is useful in clarifying key differences in the different types of innovation activities, it is not absolutely clear when some science-related knowledge interaction can be categorized as analytic and when it should be regarded as synthetic. Without such clarity it is difficult to use these concepts for analyzing the research question of the present thesis: how scientific knowledge becomes useful and relevant for practice. The need for developing a clearer conceptualization for this purpose is argued for below.

According to the interpretation of Manniche (2012, 1826), "knowledge dynamics can be defined as 'analytical' not because they occur in a university or the R&D department of a company but only if they follow (more or less strictly) scientific principles". Thus, if following scientific principles makes knowledge creation analytical, then all research-based knowledge should be analytical. This seems not to be the case, however, as also synthetic knowledge creation is argued to occasionally draw on scientific research and develop linkages with universities, albeit "mainly in the field of concrete knowledge application" (Asheim et al. 2007, 663).

The question that emerges is how, exactly, analytic scientific knowledge creation differs from synthetic scientific knowledge creation if the context of the knowledge creation (such as the university) is not the differentiating factor? What are the "scientific principles" that make knowledge scientific in the analytic sense? It seems that if the synthetic use of science is more concretely tied to application, then the analytic use of science should be less concretely tied to the development of applications. Such a differentiation is difficult to make in practice, however. There might be some "analytic" innovations that are based on basic research generated without any thought being given to the potential practical uses of the results. But there are also innovations that aim both to advance science and to solve concrete problems, such as Louis Pasteur's research which advanced the theory of microbes and also produced the pasteurization technique for the preservation of milk (Stokes 1997). The differentiated knowledge bases approach does not clearly indicate whether the knowledge interactions would be of the analytic or the synthetic kind when a scientist's research is influenced by the potential uses of the results.

Another claimed difference between "analytic" and "synthetic" knowledge creation is that the former focuses on "know-why" and the latter on "know-how" type of knowledge. Could this be the difference between the "analytic" and the "synthetic" uses of science as well? Here, the situation seems somewhat asymmetrical: while it is conceivable that the principles of, for example, mechanical engineering are so well understood that no further explanations (know-why) are needed, it is difficult to see this as a reason for know-*how* being any less important for analytical industries than for synthetic industries. For example, the core scientific methods of biotechnology and molecular biology (e.g. gel electrophoresis, PCR) require perceptual-motor skills and cognitive skills (i.e. know-how) just as much as or even more than they require knowledge of the know-why kind (Sahdra and Thagard 2003).

However, if one uses the drug discovery company as the archetypical example from an industry with an analytical knowledge base (as in Table 2), the role of know-how might seem smaller: in this multi-billion business the know-how of drug target screening is increasingly incorporated into automated instruments and techniques, whereupon the human know-how required to use these instruments and techniques in a sensible manner comes close to know-why.[4] Nevertheless, in most cases and phases of science-based innovation hands-on research has not been automated to a similar degree, and so the role of know-how remains extremely important for knowledge creation. It seems that in the differentiated knowledge bases approach it is not clear where to draw the line between the kinds of science-related knowledge interactions that involve purely the know-why type of knowledge and those that involve the know-how type of knowledge—nor how to account for those science-related interactions that involve both knowledge types.

Summing up, the analytic/synthetic dichotomy does not allow for teasing out the distinctions between different scientific knowledge interactions in a clear-cut manner. Calling for refined distinctions between scientific knowledge as an accumulating body of disciplinary information and scientific knowledge as a knowledge of methods may seem exaggerated, when everyone knows that the production of scientific information requires methods. Preciseness is needed, however, to ensure that different researchers interpret the terms and typologies in the same way when the differentiated knowledge bases approach is used to study science-related knowledge interactions in innovation. Otherwise consensus can be reached through negotiation among connected researchers (see Manniche 2012, 1833-34), but the interpretation of the use of the terms by unconnected researchers may vary, making comparisons between research projects more difficult.

All in all, both the above scrutiny of the differentiated knowledge bases approach and the discrepancy found between the theoretical claims and empirical indicators of the STI mode (Section 2.3.3) warrant a closer inspection of the

4 This is evident, for example, in Eisenstein’s (2006) treatment of microarray techniques used in drug discovery.

types of scientific knowledge used in innovation. This suggests the following sub-question:

3. *What types of scientific knowledge are involved in technological development?*

This question is especially addressed in the third and fourth separate studies (AM1 and AM2) of the present thesis.

2.3.5 From scientific knowledge to science-based innovation

Various conceptualizations have been created to study knowledge-related interaction between universities and industrial companies. This section reviews how these prior approaches characterize the process(es) in which the usefulness of scientific knowledge becomes recognized from the point of view of practical and economic relevance.

Phil Cooke (2002; 2004) makes perhaps the most focused effort to conceptualize the process in which science and its use meet. In the Regional Innovation System (RIS) approach developed by Cooke, this process unfolds between two subsystems of the regional system: universities and other public research organizations belong to the "knowledge generation and diffusion subsystem" of the regional innovation system, while firms belong to the "knowledge application and exploitation subsystem" (ibid., 137). In line with March (1991), Cooke considers knowledge creation in universities to be of an "exploratory" nature while knowledge application in firms is characterized as "exploitative" (Cooke 2004). An interesting question in this context is how these two forms of knowledge relate to each other.

Cooke presents two answers to this. The first involves introducing a third type of knowledge, "examination" knowledge (Cooke 2005a), which mediates between the other two. The respective knowledge creation processes are prototyping, trialling and testing. However, this perspective leaves unanswered why the results of some explorative processes are subjected to examination processes while others are not. Approaching the issue from the second angle, Cooke (2004) argues that the conversion between exploration and exploitation, between science and practice, takes place through the *linkages* between the two subsystems. These linkages can be either entrepreneurial (such as business angels, venture capitalists, and academic entrepreneurs) or institutional (such as incubators, knowledge transfer agencies and research consortia formed by public and private actors). These linkages actively mediate knowledge between scientific research and practice, especially in the case of biotechnological knowledge:

> *Moving interactively among science and research as exploration knowledge, on the one hand, and innovation and entrepreneurship as exploitation knowledge, on the other is a moderately exact analogue of moving between implicit or tacit, and explicit or codified knowledge where raw, unformulated findings translate into concrete products available on markets. So translation is the key to innovation. But translation is not automatic; it is rather the exercise by a capable intermediary of complicit understanding and expression of the two 'languages' in question. Complicit in the sense of knowing the meaning of one kind of discourse and being capable of rendering it retaining that meaning into another, different discourse. Of course, it is said that one definition of poetry is that which gets 'lost in translation' so it is not a perfect match but anyway this complicit and translational dimension is the missing element in the articulation of a full understanding of proximity-innovation articulations. (Cooke 2008, 15)*

Thus, in the RIS approach, the practical relevance of scientific knowledge is conceptualized as being implicit in scientific findings. Their practical relevance becomes explicit when intermediaries "translate" the knowledge to the language where the commercial potential of the knowledge is visible, by using their own "complicit" knowledge. Essential in this translation are the hybrid skills and languages (Cooke 2005b, footnote 26; Cooke 2007) of the intermediaries. The notion of complicit knowledge in RIS, however, seems to remain a proposition or an impression that has emerged as a side result to other research. There seem to be no empirical micro-level studies on the formation and use of complicit knowledge, nor on any other potential practices of intermediaries that would bring forth the practical relevance of scientific knowledge.

There is, however, empirical research showing that the recognition of the practical relevance of knowledge does not necessarily need complicit knowledge of the intermediaries but may come up also in the context of public research, even in the university. This is convincingly shown by Moodysson et al. (2008) in a study, which applies the differentiated knowledge bases approach to three science-based innovation projects. While this study focuses on analyzing the proximity requirements of the knowledge generation rather than on explaining how the practical relevance of knowledge was created, it nevertheless shows that the university scientists are clearly capable of realizing the practical implications of their research and of working actively to develop commercial solutions based on their research. The overall finding of the study by Moodysson et al. (2008) is that companies have to rely on the proximity between knowledge-creators specifically in the synthetic phases of innovation development but less so in the analytical phases. Yet, interestingly, scientific knowledge creation and sourcing appears to require close proximity in the very early phases of the innovation process, precisely when the practical implications of scientific knowledge are beginning to surface. This indicates that the nature of analytical knowledge creation is somehow different in this phase than in the later phases of the innovation process. This warrants further study.

Jensen et al. (2007), who introduced the STI/DUI approach (see 2.3.3), implicitly regard the firm, rather than some intermediaries or university researchers, as the mechanism, which combines scientific knowledge (or rather STI, the scientific mode of working) with DUI, the practice-based mode of working. However, the STI/DUI approach does not elaborate further on how this would happen within the firm. The combining of the two modes is "black-boxed" into an ability that the firm either does or does not possess.

Also the differentiated knowledge bases approach "lacks a conceptualization of the steps and governance mechanisms through which organizations generate, adapt and finally utilize knowledge through interaction within and across differing knowledge bases" (Manniche 2012, 1827). However, in a recent paper, Asheim (2012) seeks to resolve this issue by integrating the differentiated knowledge bases idea with the STI/DUI approach. He argues that the STI mode and the DUI mode are both possible in all of the three knowledge bases, rather than STI relating exclusively in the analytic and DUI in the synthetic knowledge base, respectively.

Asheim (ibid.) provides examples to back up his point. The first example shows the formation of the STI/DUI connection in the context of the synthetic knowledge base. In a certain engineering company, scientific knowledge is used for creating generic technology platforms in accordance with the STI mode, especially in interaction with a local university and a regional applied research organization but also with national and international universities. The platforms are then used, in interaction with the customers, to create concrete applications to solve the customers' practical problems in accordance with the DUI mode. The second example argues for another manner of forming the STI/DUI connection in the synthetic knowledge base, namely applied research in (technical) universities. The third example presents the STI/DUI connection as occurring in the symbolic knowledge base when the organizing of the design education is moved from the artesan context to the academic, for example. Asheim (2012) suggests that the formation of STI/DUI connections should be encouraged, especially with respect to the activities that are based on synthetic and symbolic knowledge bases. This could be done by providing systemic relations between public research and these activities.

The problematic aspect in Asheim’s approach is that it is difficult to use the suggested STI/DUI distinction with respect to analytic/synthetic/symbolic activities when it is not completely clear when some activities are analytic and when they are synthetic (Section 2.3.4), and what is meant by the STI mode. Jensen et al. (2007) measure the prevalence of the STI mode by looking at a company’s share of spending on R&D, the frequency of collaboration with public research, and by recognizing whether or not the company employs people with scientific training (see 2.3.3). For Asheim (2012), however, the STI mode of innovation seems to indicate only industrial collaboration with public research institutions. Given these vague definitions, the answer to the question of what mechanisms enable associating scientific knowledge with practical uses seems to boil down to the notion that the process is facilitated by increasing linkages between public research (and education) organizations and (synthetic and symbolic) firms.

Manniche (2012) pursues an alternative way in which the differentiated knowledge bases approach could be used to explain how organizations generate, adapt and utilize economic knowledge. As mentioned in the previous section (2.3.4), Manniche claims that the differentiated knowledge bases approach is empirically most useful if it is accepted that organizations may draw on multiple knowledge bases when developing innovations. He continues by arguing that having adopted this perspective, research also needs to account for “the organizational need for not only generating new knowledge but also for ’pushing’ and processing this knowledge towards commercial utilization” (ibid., 1834-5) by combining analytic, synthetic and symbolic knowledge interactions. Manniche’s suggestion is to complement the knowledge bases’ terminology with the knowledge development strategies of exploration and exploitation (March 1991; Gupta et al. 2006), with the added step of examination (which includes the testing, trialling, scoping, diffusion, contextualization and adaptation of knowledge)[5]. While Manniche’s suggestion correctly underscores the general lack of approaches that enable the capturing of the actual dynamics of knowledge processing, the value of his approach still needs to be empirically validated. As also his approach is based on the conceptually slightly fuzzy analytic/synthetic/symbolic distinction of differentiated knowledge bases, it is possible that even this more detailed research lacks the tools

5 A very similar approach has been previously developed by Cooke (2005a), who cross-tabulates abstract (rather than analytic), synthetic and symbolic forms of knowledge, on the one hand, and the concepts of exploitation, exploration and examination, on the other.

with which to unequivocally elucidate the processes in which scientific knowledge becomes pushed towards a useful application.

Summing up the discussion, the views touching upon the ways in which scientific knowledge is made relevant for technological innovation are somewhat scattered. Some of them (Jensen et al. 2008; Manniche 2012) take for granted that this process takes place in the context of (product development) firms, while Moodysson et al. (2008) show that the process may begin already in the university context. Cooke (2008) and Asheim (2012) emphasize systemic linkages between universities and companies as enabling the necessary knowledge combinations. The suggestions for the more detailed mechanisms through which the actual knowledge combinations take place are more tentative in nature, and in need of more empirical validation. Cooke (2008) suggests that intermediary agents with “complicit knowledge” perform this function. Asheim (2012) seems to suggest that such combinations take place in instances where synthetic and symbolic functions are supported with inputs from public research and education. Finally, Manniche (2012) proposes that such processes should be regarded as combinations between analytic, synthetic and symbolic knowledge bases, which are driven by the needs of organizations to explore, examine and exploit knowledge.

Given that there is no consensus over the ways to characterize the process through which scientific research knowledge gains its practical and economic relevance for innovation processes, there is a need for additional research. Most prior research proceeds from the assumption that universities conduct “disinterested” research whose practical relevance is only realized in the company context or in the interaction with companies or intermediaries. In contrast, the study by Moodysson et al. (2008) indicates that the practical relevance of scientific knowledge may be established already early on in the academic context. Due to the limited nature of attention given to such academic processes so far, the present study addresses the fourth, and final, subquestion:

> *4. How do considerations of the practical relevance of scientific knowledge enter the process of scientific knowledge creation?*

This question is especially addressed in the third and fourth separate studies (AM1 and AM2) of the present thesis.

3 METHODOLOGY

3.1 The research strategies

The phenomenon studied in the present thesis, the formation of the practical relevance of scientific knowledge, is epistemologically tricky. What counts as relevant for someone, is irrelevant for someone else. Given this, it becomes rather hard to give a definition of practical relevance. And if an objective definition cannot be given, how, then, does one recognize the creation of practical relevance when one sees it? Basically, the research conducted for the present thesis in interested in *the activities of people who appear to be trying to use scientific research to accomplish something in practice*. It is assumed that the practical relevance of science forms in such processes.

The processes where scientific knowledge becomes part of technology development show the actors as they begin to add something new to the world or change something that already exists. When the research topic is viewed in this way, quantitative methods are obviously unfeasible (cf. Morgan and Smircich 1980, 498). One might define indicators for the practical relevance of scientific knowledge, such as the amount of external funding for university research, or the number of university-industry collaborations, licenses, or patents. Even the appearance of a science park that overlaps with the university campus can be seen as an indicator of increased practical relevance being attached to university research, but indicators like this cannot be used to explain *how* the underlying relevance emerges. It would be better if such explanations were in place before the indicators are chosen. As with all qualitative approaches, these explanations cannot be directly generalized and projected onto other cases and contexts, however. Qualitative research can be applicable to other cases only through the conceptual tools provided and through the interpretative work done by the analyst. The research strategies chosen for the present thesis aim at providing some conceptual tools, as well as enough contextual information for subsequent research to assess which of the present findings are related to their unique contexts and which have more general relevance.

Providing explanations as answers to ‘how’ questions requires careful scrutiny of the processes in their specific contexts. In the present thesis, explanations are presented in the form of historical narratives. While the regional perspective, the innovation process perspective and the scientific research perspective represent very different levels in the science-innovation nexus, they can all be approached with rather similar narrative approaches, because all cases involve people with distinct interests and intentions of making scientific research serve practical ends. They are trying to realize these very interests while circumstances, resources, and technologies put limits to their possibilities to do so.

Process analysis builds on events sequence data, which is used to analyze how development and change unfold (Poole et al. 2000). Even though all the empirical studies of the thesis rely on such events sequence data, the research strategies employed were somewhat different in each empirical case. The first article (co-authored A1) in this thesis seeks to compare different potential theoretical explanations for the emergence of a science park. This resembles the *within-case process tracing* method elaborated by Bennett and Elman (2006), where each significant step toward the outcome is explained by reference to a theory, and several alternative explanations are tried. In our case, we contrasted explanations from systemic, constructivist, and actor-network perspectives with each other and found that especially the systemic account left out critical features and steps of the process. The two other approaches could be shown to provide richer, complementary accounts.

The research strategy behind the second article (co-authored A2) was an *intensive case study* of an on-going innovation process with radical ambitions. Such an approach follows the “thick description” (Geertz 1973) principle, where the details and multi-faceted features of a unique or extreme case are gradually crystallized into a coherent interpretation (see also Flyvbjerg 2001). We were not without theoretical preconceptions, however. We had recognized that the case seemed to be a powerful example of interplay and even conflict between a high-tech innovation process and the so-called socio-technical regime (Geels 2004). This was evidenced, for example, by the exceptionally long time span of the case without an as yet determinate outcome and the hostile, rather than merely disinterested, reactions from the incumbent firms in the relevant industry. The theory of system innovations and socio-technical transitions (Geels 2005; Geels and Schot 2007) characterizes the innovation-regime tension in an abstract level or through historical examples, but there is very little knowledge of how the on-going efforts to break (into) the regime appear at the level of the actors when the process is still unfolding. So we used an in-depth case study to illuminate the conflicts and solutions between an innovation process and the intended socio-technical environment of the innovation in a case where these challenges seemed to be particularly accentuated.

Epistemologically, the first and the second article manuscripts of the thesis form a pair. The research question of the latter—how considerations of practical relevance enter into the process of scientific knowledge creation—

necessitated a conceptual approach that did not exist yet, so it had to be developed first. In reality, this need was only realized after the first round of interviews had already been conducted for the final empirical study. The original intention was to use the differentiated knowledge bases approach (Asheim and Gertler 2005; Moodysson et al. 2008) to analyze the data. When it became evident that a more nuanced set of concepts will be needed to answer the research question, the preliminary data was put on hold without further analysis, and the required theoretical work was done solely based on literature. The interviews already conducted possibly influenced the way in which the important themes from the literature were recognized. However, the development of the conceptual framework did not involve generalizing from the cases (Eisenhardt 1989); it involved conceptual and theoretical analysis, building on prior theorizing.

As the conceptual framework became available, it was natural to apply an *extensive case study* approach (Stoeker 1991) to answer the final research question. This entailed mapping common patterns and properties across cases (Ericsson and Kovalainen 2008) in order to test the robustness of the conceptual categories just developed. The original case descriptions were much “thinner” than those developed when utilizing the intensive case study method, meaning that the context of the cases was analyzed in a less detailed manner. The data gathering was more directly focused on the theoretical issue investigated. The fourth study did not only test the suitability of the concepts to the cases, but also used the conceptual pre-understanding to analyze the dynamic question of how considerations of practical relevance enter scientific research. Based on the work done for conceptual development, I expected to see a frequent alteration between different knowledge dispositions to be involved in the production of scientific knowledge with practical relevance. But the empirical research showed the issue to be somewhat more varied. In fact, the most apparent shared feature between the three cases was that the emergence of knowledge of practical relevance was preceded by the application of research methods that were new in a specific disciplinary context.

Table 3 below summarizes the research strategies and methods employed in the individual articles and manuscripts.

Table 3 Research strategies, methods and data utilized in the individual studies.

Choices in the articles/ manuscripts	***A1***	***A2***	***AM1***	***AM2***
Perspective	Regional development	Innovation development	Scientific knowledge development	
Purpose of analysis	To explain the emergence of a science park facility	To analyze the challenges that a high degree of novelty presents to science-based innovation development	To conceptualize the scientific knowledge types from the perspective of technological innovation	To study how knowledge created in university research contributes to the innovation process
Research strategy	Within-case process tracing	Intensive case study	Taxonomical development	Extensive case study
Method	Document analysis, interviews, triangulation (single process analysis)	Document analysis, interviews, triangulation (single process analysis)	Conceptual analysis Thought experiments	Document analysis, interviews, triangulation (analysis of three processes)
Empirical data	Minutes of meetings, internal reports, policy documents, newspapers, interviews	Internal reports, letters, emails, technical data, patents, plans, memos, interviews	--	Interviews, scientific publications, patents, newspapers, company web pages

3.2 The research processes

3.2.1 Article 1

The principle method applied in this case study, as well as in the other case studies of the thesis, was typical for historical analysis: assessing the internal and external validity of various sources and triangulating the evidence (e.g. Tosh, 1991). As my topic concerns recent history, I also had the benefit of being able to use interviews (Kvale 1996; Silverman 1993). The empirical material of A1 also contains a significant number of interviews done by my other co-author, who had studied the more recent stages of science park development in Turku. The material that I collected concerned mostly the planning stage of the science park project. Nevertheless, this material relating to the early phase proved to be quite central for A1 as well as for the more general argument forwarded in the present thesis, so what follows concerns only my part of the data collection.

The data collection began with preliminary interviews with two coordinators that were involved in the planning and functioning of the science park.

The purpose was to identify the main actors that had been involved and the various types of documents that had been archived during the project. The documentary material consisted of the minutes of various meetings on different forums, related strategy documents and commissioned reports, evaluations and plans, as well as various kinds of brochures. Additionally, I went through the volumes of the main local newspaper Turun Sanomat that concerned the time of the study and collected the related news systematically.

In tracing the process of negotiations and decisions, the minutes of the various related meetings played a central role. A large part of the relevant minutes were in public archives, but some of the most central ones—the minutes of Uuden teknologian säätiö (the Foundation of New Technology)—were property of private parties, who kindly granted access to these sources. Based on the documentary material, I constructed a timeline of the events that appeared to be connected to the emergence of the science park. A schematic story started to emerge. From the documents it was relatively easy to reaffirm who were the key people and organizations. The activities of university and city actors were rather well documented in the publicly available archives. Due to the contested nature of the project within the universities, one of the key meetings had even been recorded and transcribed. Apart from the participation of the construction entrepreneur in multi-stakeholder meetings, documents concerning the activities of the local construction company that built, rented, and sold the science park facilities were unavailable. In this case additional data was acquired only through interviewing.

After identifying the key actors by using the preliminary interviews and documents, I designed semi-structured interviews in which I asked the different stakeholders involved to give their version of the story. None of the approached stakeholders declined, but one key actor was unavailable due to old age so I had to ask about his role through the other interviews. There were seventeen face-to-face recorded interviews and three interviews over the phone of which only notes were taken. With the interviews, I specifically aimed at filling in the gaps that the documents could not answer, but I also could use the timeline to make follow-up questions whenever there was a mismatch between the story “told” by the documents and the ones remembered by the interviewees. After the interview process, I wrote an extensive case description, triangulating between various sources. When it was done, I let the key informants comment respective sections of the draft. There were no significant differences in my views as the analyst and the interviewees’ views. The case descriptions were then complemented with material from my co-author’s interviews, and the result was used for doing the actual analysis in which the case was re-interpreted from the three theoretical perspectives.

3.2.2 Article 2

The access to this case was granted by the fact that the main innovator behind the case is my father. After a few years of standstill, he moved the innovation project from the capital region to the context of Turku Science Park in 2005 where a start-up company was established to develop the innovation, whereupon I started to consider the possibility to investigate the innovation project as a part of my thesis. Karra and Phillips (2008) note that autoethnographic research has as its strengths the ease of access, reduced resource requirements, the ease of establishing trust and rapport, and reduced problems with translation. They list as the challenges the lack of critical distance, role conflict, and the limits of serendipity (meaning that one's case might not be very interesting to outsiders). The last one of these seemed not to be a problem: colleagues and the anonymous reviewers of the article draft confirmed that the case is exceptionally interesting. The sheer amount of uncontested patents and the ongoing nature of the innovation process are indeed features that are hard to find, let alone get access to.

What comes to critical distance, I did my best to establish it by inviting a senior colleague from another university as my co-analyst and co-author. Even though the original case descriptions were very much structured after the account given by my father (as he is the only person who has been involved in all of the phases of the development), he did not very much approve of the eventual interpretations we published. He thought that our emphasis on the ambiguity of the innovation process was wrongly chosen, and that we failed to say what was really essential. This can be taken as an indication of the fact that critical distance was successfully maintained despite me being a relative.

As to the benefits of the situation, I indeed had very good access to the case. Even though only the last two years of the forty-year process were investigated with autoethnographic methods, the trust and rapport with the more long-time stakeholders was probably easier to establish from this particular position, too.[6]

For practical reasons, I took the main responsibility for collecting and organizing the data. As the innovation development had been going on since the 1960s and in various organizational contexts, there was plenty of existing ma-

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6 There was one exception, though. One of the two managers of the science park incubator (in which the project was based at the time I did the research) saw me more as someone evaluating their work rather than someone doing academic research. He was very careful in his comments. He assumed that I was critical of the meager financial support that the project had received through the incubator. I could not get him to lower his guard, but while "defending his position", he nevertheless provided a very valuable perspective on how extraordinary and incredible the "ramblings of a mad inventor" (my father) sometimes can sound to the ears of an outsider who has not "converted" into believing the value of an invention.

terial at my parents' house, where my father had archived all the related material he possessed: 112 folders of paper from the time before personal computers (patents, patent and funding applications, contracts, reports, inquiries, technical reports and data, correspondence and newspaper clippings), and some 4,000 entries (similar material, plus emails and web links) on the hard drives of various computers. This wealth of data somewhat remedied the fact that I did not get interviews from the early stages of the project.

Due to the wealth of empirical material, we used interviews mainly to investigate the more contemporary and controversial phases of the project. During the first twenty years, the project evolved as an industrial development project in the context of three different companies. Around the year 2000, however, it was transformed from an industrial research project to a project without funding or a corporate home. The ensuing period marked a time when the most intensive conflicts of interpretations concerning the usefulness or uselessness of the innovation took place. The rather straightforward story broke into various perspectives, and the innovation appeared promising or failing, depending on whom you talked to. The interviews focused on the period starting from this point, as there was great ambiguity concerning the nature of the innovation being developed as well as why the development process was so difficult.

The analysis was very intensive joint work between us authors. The sources and case descriptions were discussed from the validity and reliability points of view, as well as with respect to the arguments we wanted to convey to the reader. Interviews were analyzed by content, and the views of different actors were systematically compared. Further data and method triangulation was used when comparing the interviews and documents (Denzin 1989) to the interviewees' comments to our case descriptions. My co-author led the development of the theoretically informed analytical framework, which emerged as we reflected on what we had learned from the case against the backdrop of the broader literatures on innovation development, such as the possibility to regard innovation as a "journey", characterized by contingency but equally as much by the accumulation of solutions and experience (Van de Ven et al. 1999; Sorensen and Williams 2002; Pollock and Williams 2008) and the possibility to discern from that journey the gradually changing visions and re-evaluations, material realizations of R&D, organizational contexts and scenarios of the future (Latour 1987; Hughes 1988; Russell and Williams 2002). We divided the case history into three periods and analyzed the developers' understanding of the innovation-to-be through the analytical framework.

The main innovator (my father) was formally interviewed eight times, and the other stakeholders once or twice. Most of the interviews with the main innovator were needed to get those parts of the storyline straight that could not be resolved on the basis of documents alone. Some of them, as well as the other ten interviews with the various stakeholders (company workers, founders, and science park administrators as well as some otherwise involved people) were especially useful for developing the more general arguments of the paper. These arguments benefited especially from the various views and attitudes held by the different interviewees towards the project and the intended uses of the eventual innovation.

In addition to the documents and the total of eighteen semi-structured interviews of one to three hours in length, dozens of email exchanges as well as informal chats and short conversations over the phone and face-to-face with various stakeholders were used to illuminate some more specific questions that came up in the joint discussions between us authors. From 2005 onward, we also had notes from the direct observations of some of the meetings, funding negotiations, technical work, et cetera, as I had been an observing and commenting participant in some instances of the project. I joined the innovation development company in question as a board member in October 2008, at which point my co-author and I were already doing revisions demanded by the journal reviewers of the article. We still added some empirical details to the analysis during the revision process, but these additions mostly concerned the earliest stages of the development in the 1970s and 1980s. We did not extend the analysis to concern the period during which I was more closely involved in the development.

3.2.3 Article manuscript 1

The development of the framework in AM1 did not follow any pre-given theoretically grounded approach to conceptual development. The guiding principle was to read what had been written about knowledge typologies, the relation between science and technology, science-based innovating, and the contribution of university research to the society, and to try to relate those ideas to each other and formulate concepts describing scientific knowledge and its relation to technology development so that the overall result remained internally consistent.

In developing the framework, the following sources provided the main building blocks. My starting point was Arthur’s (2007) definition of invention, which formed the core of my understanding of the use of knowledge for technological purposes. Asheim and Gertler’s (2005) views on differentiated knowledge bases had become familiar to me through the excellent innovation process analysis by Moodysson et al. (2008). The application by Moodysson et al. (ibid.) clarified the differences between science-based and engineering-based modes of work, and especially the role of optimizing through trial and error in the latter mode. The views of Stefik and Stefik (2004) on the nature of breakthrough innovation helped to further elucidate two important dimensions of research: what is needed and what is possible. Upon encountering Donald Stokes' book *Pasteur's quadrant* (1997), I understood that I was in a way elaborating on Stokes' model; I wanted to understand more in detail what happens "within" the Pasteur's quadrant where knowledge creation is driven both by the search for fundamental knowledge and the considerations of use of that knowledge (the upper right quadrant in Figure 2).

		Considerations of use?	
		No	Yes
Quest for fundamental understanding?	Yes	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
	No		Pure applied research (Edison)

Figure 2 The quadrant model of scientific research (Stokes 1997, 73).

At the same time, I felt that some important ingredient was still missing from the overall framework of Stokes. It seemed to have something to do with the blank bottom left corner of his quadrant model. A paper by Shinn and Joerges (2002) on research technologies was eye-opening when I tried to figure out what aspect of science could concentrate on research which does *not* aim at a fundamental understanding *or* external-to-science uses. Stokes' idea of purely empirical research without scientific ambition did not feel right. Upon reading the paper by Shinn and Joerges (ibid.) against the framework of Stokes (1997), it dawned on me that the development of research methodologies must be absolutely crucial for the advancement of the empirical part of science, yet this activity does not need to directly aim at new scientific theories or external-to-science applications.[7] The methodological aspect subsequently became the bottom left quadrant of my framework. Later I used the de Solla Price's (1985) idea of "instrumentalities" to further differentiate between methodological skill and the invention of new methods.

The final solidifying ingredient in the conceptual framework came from Aristotle's way to discuss knowledge. Some sources that I had encountered (Asheim et al. 2011; Gorman 2002; Johnson et al. 2002; Lundvall 1998; Mokyr 2002), referred to Aristotle's categories of knowledge. It felt important to see for myself what Aristotle had said. I could only read English and Finnish translations, but it seemed to me that Aristotle was expressing something very interesting that had not become evident through the references to his texts, namely that the virtues of knowing—as Aristotle presents them in his *Nicomachean Ethics*—have three aspects: outcome, activity (knowing), and a third ingredient that involves motivation and a direction of the search for knowledge. The concept he uses of the different virtues of knowing is often translated as "disposition", which is the word I also chose to use. Depending on the context, Aristotle emphasizes any of the above-mentioned three different aspects of disposition, whereas I chose to use the term solely in its most elusive meaning, the one referring to motivations and directions.

The structure of the framework was built on these foundations, while the other sources helped to validate and refine the terminology and to rearrange the relations of the concepts until they felt internally consistent, and until further readings did not produce more theoretical or conceptual observations that would have given rise to a need to modify some aspect of the framework. In practice, this work was organized by a continuous mapping of the theoretical observations into a conceptual diagram. One of the early versions of the diagram is presented below (Figure 3). In this early formulation, the vertical dimension of the diagram is based on Asheim and Gertler (2005), the horizontal dimension on Stefik and Stefik (2004), and the *italicized* terms are derivatives of Arthur's (2007) definition of invention. The bolded terms are my own definitions. At this point, the left half of the figure was still a conceptual mess, while the right side already began to have the correct ingredients in place, albeit in a skeletal form.

7 This was a situation where the prior data collection for the final study supported the conceptualization, even though I consciously left the empirical testing of the framework for later. Upon reading the paper by Shinn and Joerges (2002), I could finally understand and label my father's activities in the university in the 1960s: he was trying to develop research methods (see section 3.2.4).

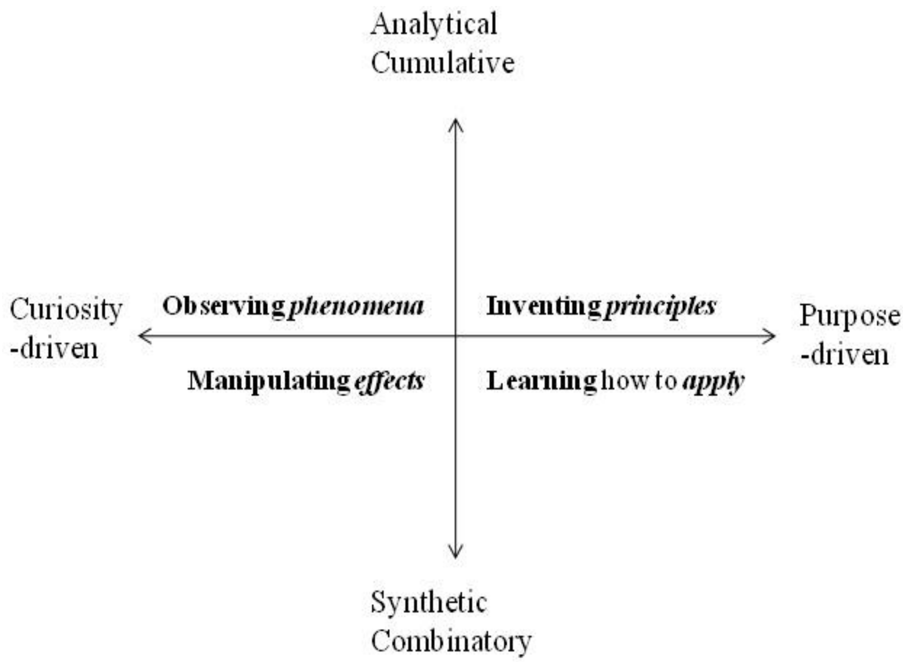

Figure 1 Developing the conceptual framework through mapping the relations between the terms into a diagram: an early version.

As the reviewing proceeded, I continuously adjusted the axes and the terminology of the diagram so that internal consistency was retained. Since the early stages of this practical method of conceptual development had processed the literature predominantly through thought-experiments (Weick 1999) and visualization, it was challenging to deconstruct relevant parts of the work into a narrative form that could be conveyed to the reader as a scientific journal article. However, the conversion of the ideas into narrative form also helped finalize the framework. Only when I attempted to verbalize the relation of tacit and explicit knowledge in the suggested framework, did it appear necessary to distinguish between (propositional) scientific knowledge and research skills (procedural scientific knowledge).

3.2.4 Article manuscript 2

The criteria for choosing the cases for the analysis reported in AM2 were the following. I wanted to study scientific research that had given rise to radical innovations in the sense defined by Garcia and Calantone (2002), meaning innovations that were both technologically novel and created a new market. The underlying reason was that I felt the sources of such innovations to be under-researched from the regional development point of view. This choice obviously limits the value of the analysis from the perspective of those cases and instances where scientific knowledge is in a supporting rather than initiating role in technological innovation processes. But even though the chosen cases are, in a sense, examples of the much-criticized “linear” model of innovation (Balconi et al. 2010), I felt it important to understand also the emergence of these types of innovation even though they probably are much more rare than the innovations where the role of scientific research is smaller.

I also wanted to study cases that had emerged from academic research conducted in Turku, due to the ease of access and because the other case processes studied in my thesis research were also for the most part situated in the Turku region. This choice means that the influence of institutional conditions giving rise to science-based innovations cannot be assessed, as the three cases to some degree shared the same institutional context, even though they unfolded in different decades.[8] However, the shared context enhances the comparability between these cases. Medical research was chosen as the empirical context, as it often involves opportunities for both creating new knowledge about natural phenomena and applying this knowledge for some practical purpose. The cases were selected so that they were likely to display the different types of knowledge (as defined in the conceptual framework in AM1). Two of the three cases initially involved elements of more “basic” science, while the third case was application-oriented to begin with.

For methodological reasons, the focus of the analysis was put on the trajectories of individual researchers rather than on those of larger research teams. The exploratory nature of this study called for a research setting in which the different knowledge types can be discerned as simply as possible. This is most easily studied with respect to changes in the research interests of individual researchers. This may lead to an over-emphasis of key individuals in the creation of new knowledge, but it enables capturing the multi-faceted nature of the knowledge produced.

The data for the analysis was drawn from two kinds of sources. First, three rounds of interviews were carried out with the inventors. The questions of the first round were open-ended, but in the later rounds, the questions were increasingly structured. The interviews lasted between one and a half and three hours. Two of the interviewees were over 70 years of age, although not fully retired from research (one of them was, again, my father). Their seniors could

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8 For an interesting, related study focusing on the institutional conditions giving rise to scientific discoveries, see Hollingsworth (2006).

not be interviewed anymore. One of the interviewees was under 50 years of age. His closest senior was still available and was, thus, also interviewed, once. Additional background information was gathered from newspaper and Internet sources.

The second major source consisted of the researchers' publications, i.e. journal articles and patents. One of the researchers (my father) published only one journal article before becoming a full-time inventor (some 30 inventions by May 2012), one has published only scientific papers (315 by May 2012) and no patents, and the youngest one has been active in both fields (365 scientific papers, 16 inventions by May 2012). The full-time inventor's personal archive—plans, technical reports, instrument testing data, and some correspondence—substituted for the lack of scientific publications. The titles of scientific publications, the Finnish and U.S. patents, as well as the patent applications of each study subject were put into chronological order and the apparent main research interests and changes in them were developed into a rough timeline. The timeline was supplemented with a more detailed analysis of the abstracts of journal papers from the first publication until five years after the first invention, as well as by the full text of the patents and patent applications that were created during that period. This analysis was further supported by taking into consideration review papers that described the evolution of these particular fields of science and technology.

I divided the analysis into two phases: the analysis of the research that preceded the emergence of the invention and the analysis of the inventing and the follow-up research. I chose this narrative structure to highlight the differences between knowledge that is, as yet, not focused on any certain instrumental principle, and knowledge that concerns a specific technological solution. The narrative of AM2 also includes short paragraphs (in *italics*) describing the "Eureka moment" of each inventor "as it happened". These are composed on the basis of the inventor descriptions during different interview rounds. The inventors have confirmed that these narratives adequately match their recollection of the incident.

The case that concerned my father's research activities in the university context in the 1960s was the one leading to the development of the Sample Oxidizer, which was the predecessor to the innovation project analyzed in A2. In the analysis of AM2, the precaution against the potential lack of critical distance was to analyze all cases in a similar manner. Being related had at least one consequence, though: one night when I was visiting my parents, my father utilized the opportunity to reflect extensively on the tables that summarized the analysis in AM2. The other researchers whose research trajectories I had analyzed had also been given a chance to comment on the manuscript before submission, but they had made only small remarks concerning the correct representation of the facts of the case, and had not commented on my analysis. I felt that my father’s comments and questions concerning expressions that he could not comprehend in the tables were helpful for making the different cases more comparable and hopefully more understandable, too.

4 RESULTS

4.1 The articles and article manuscripts as individual contributions

Despite sharing a background interest in the formation of the practical relevance of scientific knowledge, the individual papers address different academic audiences. Therefore, before going to the results of the thesis, this section gives a brief account of the main arguments of the paper and their respective, specific audiences.

A1 is targeted at those interested in alternative ways to explain the emergence of a regional infrastructure for innovation, and it compares the analyses produced through three different analytical frameworks. The systemic account is found to over-emphasize the role of policy. The social constructivist account is found to reveal the boundary object nature of the science park project being studied. The networking perspective reveals how the participation in the science park project offered possibilities for empowerment to the members of the network (especially to the academia and the policy actors). In other words, on the surface, it might seem that the national policies for supporting biotechnology development led to the rapid emergence of the science park. However, the analysis of the paper reveals that when one takes a deeper look into the underlying processes, it becomes visible that the development was only possible because locally pre-existing networks reacted to the national biotechnology policies, found each other, lobbied the policy-makers, enrolled supporters for the cause—and accepted the situation when the new supporters (the city, the national Ministry of Education, and local universities) began steering the project, even if it signified a partial differentiation from the original aims.

Thus, the analysis demonstrates that a process account is necessary to understand the mechanisms of regional adaptation. In a more detailed level, the analysis shows that science parks may be mechanisms of regional adaptation, not only through their functioning, but also through the process of creating them. This process may change the regional culture of collaboration. Finally, the analysis claims that self-organized activity and related personal networks and trust are important for the success of regional development initiatives. The article comments specifically on the triple helix discussion: in the studied case, and in contrast to the usual argument of the Triple Helix approach, there was little overlap in the roles of the government, university and industry parties. Rather, these learned to align their activities with respect to each other.

A2 approaches those interested in the management of radical innovations, by investigating what the challenges involved in developing them are. The findings indicate that the first challenge is to understand the level in which the innovative solution is different from and discontinuous with the existing solutions. The second challenge is to present this mismatch as smart innovativeness and not as a strange deviance from the conventional way of doing things. The analysis highlights that, in addition to technical and resourcing hurdles, “conceptual discontinuity” may be a significant source of ambiguity and uncertainty in radical innovation projects. The study produces new empirical knowledge, as the analyses of ongoing innovation projects with radical ambitions are rare, if not non-existing, in the innovation and management literature. The discussion of A2 claims that the prior management research on radical or disruptive innovations as well as on strategic niche management and transition analysis fails to recognize the sources of uncertainty and ambiguity that are inherent in radical innovation processes, especially in their early phases. Another argument of A2 is that the existing “innovation coaching” tools would benefit from the analytical approach employed in the article.

AM1 seeks to clarify the nature of knowledge emerging in natural science research for those interested in the science-technology relationship. It seeks to create a typology of scientific knowledge. Its contribution is to clarify a number of prior discussions: With respect to the research on knowledge transfer, the approach can be used to recognize the kinds of knowledge that universities can contribute to innovation. With respect to the various knowledge typologies, the approach highlights the role of methodological skill and clarifies the type of knowledge presented by inventions as well as the differences between the research activities that are usually lumped together as representing “basic” and “applied” research. With respect to the different (linear vs. interactive) models of innovation, the approach outlines the different ways in which university research may be involved in the early stages of innovation processes.

AM2 addresses those who are interested in the role of scientific knowledge in (regional) economic development. It applies the approach developed in AM1 to study the research trajectories of three scientists in order to comment on the “learning economy” and the “differentiated knowledge bases” approaches on knowledge-based economic development. The analysis shows that university research contributes to innovation through multiple knowledge types, each with a different function. The different types combine in different ways during the actual research and innovation processes. These results are used to reveal some shaky assumptions in the prior research concerning the role of university-generated knowledge in industrial innovation. It is suggested that the approach of the paper enables a better identification of the kinds of knowledge flows taking place in university-industry relations.

A schematic overview of individual articles and article manuscripts is provided below, in Table 4.

Table 4 Overview of the research articles and article manuscripts of the thesis.

	A1	***A2***	***AM1***	***AM2***
Title	The co-evolution of the social and physical infrastructure for biotechnology innovation in Turku, Finland	The fog of innovation: Innovativeness and deviance in developing new clinical testing equipment	Knowledge types, scientific research and technological development	University-generated knowledge and innovation: The contribution of medical research to advances in health-care technologies
Authors	Maria Höyssä, Henrik Bruun, Janne Hukkinen	Maria Höyssä, Sampsa Hyysalo	Maria Höyssä	Maria Höyssä
Journal	Research Policy 33 (2004) 769-785	Research Policy 38 (2009) 984-993	Unpublished manuscript	Unpublished manuscript
Purpose of analysis	To explain the emergence of a science park facility	To analyze the challenges that a high degree of novelty presents to science-based innovation development	To conceptualize scientific knowledge types from the perspective of technological innovation	To study how knowledge created in university research contributes to the innovation process
The fields of interest of the intended audiences of the article	The Triple Helix discussion, research on regional development	Innovation management, strategic niche management	Knowledge transfer, knowledge typologies, innovation models	The learning economy and differentiated knowledge bases approaches

Whereas this section has summarized the contributions of the articles and article manuscripts for their specific audiences, the next section will re-interpret the analysis from the viewpoints of the main question and the sub-questions of the present thesis and links it with the research on regional development.

4.2 Answering the research questions of the thesis

4.2.1 The practical relevance of scientific knowledge in regional development

A1 studies the regional aspirations to enhance the practical relevance of scientific knowledge by creating a science park. The analysis shows that the broader policies and regional efforts to support the creation of practically relevant scientific knowledge is a relatively recent phenomenon in Finland, including the Turku region, which serves as the empirical context of this study. In Turku, this phenomenon was exemplified by the creation of the BioCity facility, in which the synergy between the industrial and academic parties was expected to emerge from the opportunities for easy interaction and collaboration between tenants and the sharing of laboratory facilities.

The empirical findings of A1 do not support the triple helix view of Etzkowitz and Klofsten (2005), which emphasizes the entrepreneurial university as the driver of regional knowledge-based development. In Turku, the regional interpretation of the significance of university research gained significantly entrepreneurial undertones even though the local universities were not originally involved. Even when they did become enrolled, they tended to emphasize the resources for doing academic research rather than those for ensuring science-industry interaction. The early activities aimed at enhancing entrepreneurial developments in the region were not led by the university, nor were they regionally governed. They were carried out by self-organized networks, which were of a temporary nature and tuned into local needs.

This finding has later been supported by Hommen et al. (2006). They find that political mobilizations of loose development coalitions, rather than actively entrepreneurial universities, are the key driving force explaining the emergence of a science park. Benneworth et al. (2008) also report similar dynamics in the case of Lund, Sweden, where the University of Lund was not an initiator behind the emergence or early development of the IDEON science park.

The learning curve that accumulates as different regional stakeholders jointly plan for the use of resources forms an important asset, enabling the region both to adapt to various contingencies and take further proactive initiative in the changing world. Power and Malmberg (2008) have noted that it is not a given that processes of academic knowledge creation, innovation, and industrial value creation will come together at the regional level. The analysis of A1 implies that the likelihood of such coming together may at least be improved, not only with the concrete facilities for technology transfer, but also by the communication and trust increased by the planning of the related infrastructure.

Feldman and Desrochers (2004) have found that the founding process of a university has far-reaching, path-dependent effects on the future of that organization because the institutional culture is largely shaped in the early years of the university. There is reason to suspect that, similarly, the original non-entrepreneurial cultures of the local universities would be path-dependently transferred to the shared research facility between the two universities and the regional companies that were studied in this case. The development analyzed in A1 did not lead to a significant entrepreneurial turn at the level of the local universities. And this lack of interest towards industrial collaboration made the local industries take some distance to the project, which did not bode well for the success of the eventual outcome. Yet, the representatives of the city managed to create inclusive rules for the use of the planned facilities. Simultaneously, the developments of the global pharmaceutical industry affected the local pharmaceutical companies, which downsized their research activities. This led to the creation of the first small biotechnology enterprises in Turku, conveniently at the same time as the biotechnology science park facility became ready for that particular kind of industrial activity. These two developments put a positive entrepreneurial spin on the science park project and gave it a good start. Thus, the study, on the one hand, confirms Feldman and Desrocher's (2004) notion of the importance of early culture formation and path-dependency. On the other hand, it states that original non-entrepreneurial university missions do not need to deterministically prevent further changes in the regional culture.

Methodologically, A1 makes a parallel argument with Van de Ven and Poole (2005). Whereas they analyze "organizations vs. organizing", A1 can be regarded as analyzing regional innovation "infrastructure vs. infrastructuring". Our point is that when the regional innovation infrastructure is analyzed through the system lenses of evolutionary economics, one sees changes in policies supporting biotechnology development—in other words, a "sequence of events, stages or cycles of change in the development of an entity" (Van de Ven and Poole 2005, 1387)—but when the infrastructure is analyzed through the lenses of the social construction or actor-network approaches, one sees "emergent actions and activities by which collective endeavors unfold" (ibid., 1387). The significance of this contrast is that the latter focus brings one closer to *explaining* how regions change, instead of just *describing* sequential changes in the regional system.

4.2.2 The practical relevance of scientific knowledge in innovation development

In A2, the focus is moved from the regional level to the level of the innovation process. The analysis concerns the challenges caused by the potentially radical nature of the innovation when the practical relevance of the innovation is being demonstrated.

The findings can be condensed into the following points. As noted by Garcia and Calantone (2002), radical innovation involves both technological and market discontinuity. Subsequently, there are two broad aspects to the practical relevance of scientific knowledge. On the one hand, scientific knowledge can be considered relevant if it can be used to achieve some new technical functionality. On the other hand, knowledge becomes relevant if this new functionality is considered economically valuable by those with the resources to invest in the technology. But the market relevance is further complicated by the fact that the use value and the economic value of the innovation are not necessarily identical; those with vested interests in the prevailing technologies may see little economic value in a concept that sidesteps the mainstream technologies, even if the new concept involves novel functionalities and promises to be useful from the eventual end-user point of view. The different forms of relevance affect each other in complex ways, making the management of radical innovations challenging. The first challenge is to internally understand and predict the nature of innovativeness of the innovation as well as how and at which level it is to link with the external environment and the market. The second challenge is to present this innovativeness to external parties.

These challenges are quite overlooked in innovation research in general. In particular, they are overlooked in the regional research on science-based innovative activity. The earlier research emphasizes the “analytical“, i.e. codified and transferable (Asheim and Gertler 2005; Moodysson et al. 2008; see also Lundvall and Johnson 1994) nature of scientific knowledge. A2 emphasizes the potentially ambiguous and “deviant” nature of innovation projects based on scientific knowledge. To communicate discontinuous ideas is far from communicating codified research results, but the communication challenges are not exactly due to the tacitness in the sense of knowledge being non-codifiable (Cowan et al. 2000; Johnson et al. 2002), either. Rather, successful communication requires an understanding of several aspects: for which parties the innovation is discontinuous; the levels (from principles to components, to subsystems, systems, uses and finally to socio-technical regimes) in which the product concept is discontinuous; and, the tightness of coupling required between the various parts of the innovation vs. the tightness of coupling of the part of the “regime” where the innovation is supposed to fit.

The analysis found the management challenges of radical innovation to be amplified by what we coined *conceptual discontinuity*, the lack of suitable terms and expressions to explain and contextualize the work, the components and the underlining principles in a meaningful manner that would have facilitated the understanding of the relevance of the developed solutions.

As noted in Section 2.2, the only strand of regional research that has focused on the complexities involved in radical innovation development is the recently emerged research on the geographical aspects of sustainability transitions. This body of research has raised the need to study the various scales at which transition developments take place and how actors enact the connections between the local and global scales (Coenen et al. 2012). While the analysis in A2 does not use the terminology of scales, it is explicit on the niche-regime interaction and the narrative provides empirical knowledge that illuminates the scale issue, as well. The analysis shows that radically innovative developments took place sequentially in different locations on two continents, starting from and eventually ending up back in the Turku region again. Wherever the niche was located, the development in it was predominantly local, yet linked with broader technological developments (the emergence of PCs, lasers and the Internet), policy developments (changes in Finnish and EU technology policy), and regulatory developments (the international working group that developed guidelines on future laboratory quality assurance). These international developments were followed and utilized early on. The subsequent empirical result is that niches do not only push from bottom-up, but they may develop linkages to the global scale already before they develop products and business concepts that would enable them to significantly influence the wider socio-technical regime.

The project analyzed in A2 may be a non-typical science-based project for two reasons. Not all science-based innovations face the discontinuity challenges to the same degree, even if they are technologically novel and do not address a pre-existing market. Nor do all such projects become completely detached from their original academic home (which happened to this project after the first years), thereby losing potential support and academic credibility that might otherwise be preserved. However, having knowledge of an extreme case helps in understanding the *extent* to which a high degree of innovativeness may cause problems for innovation management.

4.2.3 Practical relevance in scientific research

In the AM1, the focus is moved from the innovation process to scientific knowledge creation. The aim is to conceptualize the scientific knowledge types from the perspective of technological development. The underlying motivation is to develop a framework that enables analyzing how the considerations of practical relevance enter scientific knowledge creation. The results indicate that scientific knowledge can and should be conceptualized from three compatible perspectives (see Figure 3):

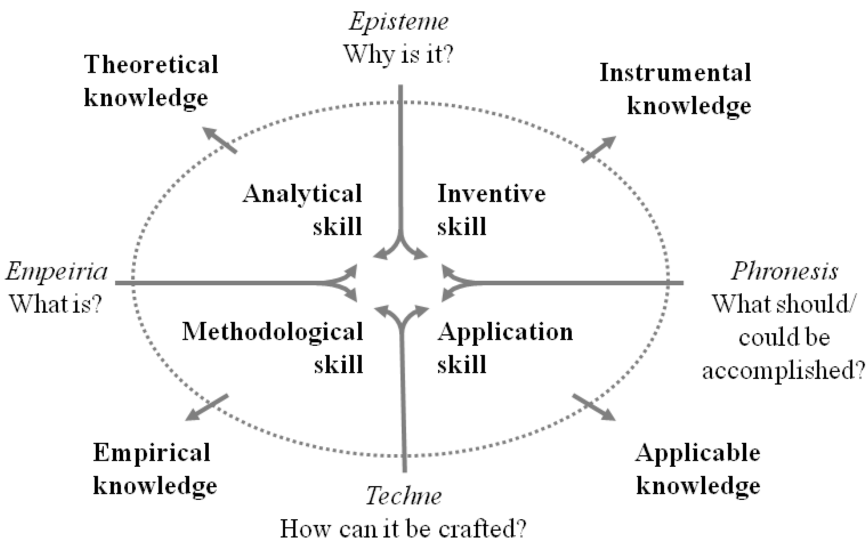

Figure 4 Types of knowledge, skill and disposition in scientific research.

1. *Knowledge* (propositional knowledge): Explicit research results, which can be codified and are often published. There are four types of knowledge:

- *Empirical knowledge*: Observations (measurements, data)
- *Theoretical knowledge*: Explanations (facts, models, theories)
- *Instrumental knowledge*: Inventions (principles of new methods, techniques, cures)
- *Applicable knowledge*: Solutions (understanding of how known principles can be put to practice)

2. *Skills* (procedural knowledge): Embodied research skills that enable carrying out the research process. While it is possible to describe and teach skills verbally or by writing, they have a tacit basis, meaning that practice is needed before one can master a skill. There are four types of skill:

- *Methodological skill*: Using scientific methods, experiments and instruments to find, measure, simulate and control natural phenomena and effects
- *Analytical skill*: Framing problems, formulating questions and posing hypotheses to explain natural phenomena and effects
- *Inventive skill:* Formulating technological and biological principles that utilize natural effects to enable new methods of utilization, observation, manipulation or control of nature, life, or information
- *Application skill*: Applying other research skills to study known technical and biological principles and the conditions in which these function, to best harness and utilize the underlying natural effects

3. *Dispositions*: The perspectives from which one approaches natural phenomena, the motivations for creating knowledge. There are four types of disposition, with an origin in Aristotle's views upon knowing:

- *Empeiria*: Seeking to understand, through experience, that what is
- *Episteme*: Seeing to understand why things are the way they are
- *Techne*: Seeking to understand how things can be crafted or manipulated
- *Phronesis*: Seeking to understand what should or could be accomplished

A full-blown theoretical model would show a core sequence around a core construct, which could be used to causally explain a phenomenon (Whetten 2002), whereas the conceptual framework and diagram present only conceptual relations without a sequence that would provide an explanation answering a specific empirical research question. The perspective from which the framework is developed is against any deterministic causal process: it does not presuppose that scientific discovery should precede invention, or that invention should trigger discovery. Rather, when one tries to fit the concepts against real cases of invention, as in the analysis of AM2, one sees that the knowledge creation along a certain research line may start from any direction represented in the model, and an invention may occur at any point in the process.

This approach gives a broader account of the nature of scientific knowledge than Lundvall and Johnson's (1994) knowledge typology, which regards scientific knowledge as being mainly of the know-why type (i.e. theoretical knowledge), with some elements of know-how (i.e. methodological skill). Further, the approach of AM1 provides, arguably, a more clearly defined account of research-based knowledge and knowing than what is provided by the differentiated knowledge bases approach of Asheim and Gertler's (2005). The latter refers to know-why, codification, and the use of scientific principles as the defining features of the “analytic knowledge base”. However, it also notes that the “synthetic knowledge base” may draw on science, although “mainly in the field of concrete knowledge application” (Asheim et al. 2007, 663). By using the approach developed in AM1, it is possible to clarify that the difference between analytic and synthetic scientific knowledge: the synthetic knowledge base draws only upon *applicable* scientific knowledge relating to known instrumental principles (such as those of mechanical engineering), while in the analytical knowledge base also new *instrumental* scientific knowledge emerging from research is important. The innovation development in both knowledge bases can interact with or employ people with various types of research skills. Contrasted with the knowledge bases approach, these distinctions can provide additional analytical rigor especially in detailed studies of scientific knowledge production and university-industry knowledge collaboration.

From a conceptual perspective, the approach developed in AM1 makes, arguably, a more accurate reference to Aristotle’s knowledge dispositions than Lundvall (1998) or Asheim (2012). Lundvall (1998, footnote 34) acknowledges similarity between know-why and *episteme* on the one hand, and know-how and *techne* on the other, noting that the correspondence is not perfect as scientific research always involves a combination of know-why and know-how. Asheim (2012, 997) comments on the distinction between *episteme* and *techne* that “[t]he former corresponds with the rationale for analysis referring to understanding and explaining features of the (natural) world (natural science/know-why), and the latter with synthesis (or integrative knowledge creation) referring to designing or constructing something to attain functional goals (engineering science/know-how)”.

Even though Aristotle’s concept of *episteme* is often translated as “scientific knowledge” (Smith 2012, section 6.1.), this translation should not be taken literally: science in the sense we know it was not known in Aristotle’s times. Aristotle was simply defining different ways of knowing, and AM1 argues that not only one but at least four of the dispositions defined by Aristotle (*empeiria, episteme, techne, phronesis*) can be involved in modern scientific research. Especially, the aspect of art or craft (making something into being), *techne*, as well as experience-based learning, *empeiria*, are present in science through the art of making experiments in which certain natural phenomena are produced and/or observed. Even though the aspect of *techne* is pronounced in engineering, knowledge of how nature can be manipulated is produced also in physics, chemistry, medicine, biology, biotechnology and materials science, for instance. In other words, art or craft does not (anymore) concern only the most tangible materials, but also molecules, electrical charges, radiation, cells, DNA, etc. It is possible to differentiate between *episteme* and *techne,* but it cannot be said that university science does not concern *techne* at all or that engineering does not concern *episteme* at all. These notions should explain why some fuzziness ensues from the attempts to separate know-why and know-how into distinct differentiated knowledge bases or STI/DUI modes of innovation.

The approach developed in AM1 involves *phronesis* as the fourth aspect of knowing involved in scientific knowledge production. This aspect is not recognized by the "learning economy" approach developed over the years by Lundvall and his colleagues[9] or the "differentiated knowledge bases" approach developed by Asheim and his colleagues. Yet, to conceptually acknowledge that scientific research may (but does not need to) integrally involve also considerations of practical uses is a more realistic account of science than the idealized ones where science is assumed to strive only for fundamental explanations (know-why).

The results of the analysis in AM2 show that the concept of *phronesis* developed in AM1 allows for studying how the practical relevance of scientific knowledge emerges during the research process. In fact, the four dispositions introduce four different kinds of relevance into scientific research. For the *epistemic* disposition, knowledge relating to explanations is the most relevant. For the *empiric* disposition, knowledge relating to experience is the most relevant. The disposition towards *techne* means that knowledge enabling the crafting of things and the manipulating of nature is the most relevant. Finally, the *phronetic* disposition associates relevance to knowledge that enables determining and acting on practical problems and aims. Thus, the research question of the thesis—how the practical relevance of scientific knowledge forms—can be recapitulated as a question of how the *phronetic* research disposition intertwines with scientific knowledge creation and the related development of innovations.

The analysis in AM2 shows that the paths through which the *phronetic* research disposition intertwines with scientific knowledge creation can take different routes. In one case, the questions posed by an industrial company triggered research conducted with a *phronetic* disposition. In two other cases, the scientists' frustration at the (badly functioning) existing solutions, which they had experienced as users, also triggered research with a *phronetic* disposition. However, all of the cases had in common that by solving the practical prob-

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9 Lundvall (1998, footnote 34) does make a brief reference to Aristotle's concept of *phronesis,* but he relates it, rather vaguely, to the ethical dimension of learning rather than takes it as an integral part of the (know-what/know-why/know-how/know-who) knowledge typology. However, it should be remembered that Lundvall and Johnson's (1994) typology is not fully comparable with the one developed in AM1, as it concerns all kinds of economically relevant knowledge, rather than scientific knowledge only.

lem, the scientists could also advance their own scientific field. Further, all cases involved the use of research methods which were new in that disciplinary context.

These results suggest that in order for science to become practically relevant, it should simultaneously remain scientifically ambitious. This can best be accomplished by extensive studies of a certain topic from the perspective of multiple dispositions. This finding stands in contrast to the argument of Cooke (2008), which gives a central position to the *complicit* knowledge of "intermediaries" between the knowledge-exploring and knowledge-exploiting subsystems of the regional innovation system. Based on the analysis of AM2, *the practical relevance of knowledge is something that is gradually built into the research* rather than interpreted from "its language" afterwards. Science policies tend to focus on adding linkages and intermediaries between academic and economic activities in order to enhance the effectiveness of the "innovation system". However, the present findings suggest that more thoroughgoing changes may be needed for science to retain its social legitimacy under the pressure to produce increasingly applicable knowledge. From the science-based regional economic development point of view, it seems that more important than the presence of "intermediaries" are the environments and institutional conditions that promote and facilitate the conducting of scientific research from the perspective of multiple dispositions, including the *phronetic* disposition.

Once such conditions are in place, however, there is need for intermediaries *who understand the technological and market discontinuities of the new knowledge* (see Section 4.2.2) and, thus, can help transform the practical relevance of scientific knowledge into the economic relevance of innovations. The usefulness of the concept of "complicit knowledge" (or, perhaps, "complicit competence") might be further improved if it were defined as the understanding which concerns the various *discontinuities* between the knowledge-based innovation process and its intended environment, and the ways to overcome them. This re-interpretation of the concept preserves the original idea of Cooke's (Section 2.3.5.) relating to the competences needed to bring scientific knowledge to the market. The suggested re-interpretation would, however, downshift the metaphor of translation and highlight the part of the complicit knower in the further production and processing of the knowledge.

Asheim's (2012) suggestion for how scientific knowledge could come to benefit innovation in companies is to build linkages between public research and companies, especially companies relating to synthetic and symbolic knowledge bases. Such linkages might indeed introduce new *phronetic* views on scientific research. One such fruitful encounter took place in one of the cases analyzed in AM2, when the points raised by a sugar company inspired academic researchers to pursue an entirely new kind of research question with unforeseen practical relevance. However, in the other cases, the *phronetic* inspiration stemmed from very concrete experiences of the scientists as users of existing technologies. The subsequent policy conclusion, thus, points not only towards intensifying the linkages between university research and industrial development, but towards intensifying the linkages between academics and the contexts of use, wherever these are located. These linkages need not be formed to formal research only. The analysis suggests that the experiences of use which is gained during one's studies may play a decisive role in—and also provide the necessary incubation time for—coming up with high quality research on topics that are practically relevant.

All innovations analyzed in AM2 are of the radical kind. While they were not new general purpose technologies (Bresnahan and Trajtenberg 1995) such as the Cohen-Boyer technique, the method of DNA cloning, they nevertheless were radical in their time in the sense of involving entirely new technology and creating a whole new market (Garcia and Calantone 2002). Thus the analysis of AM2 does not directly answer how scientific knowledge becomes relevant for *incremental* innovation development. In terms of the conceptual approach, incremental innovation development involves modifying some existing instrumental principle. Thus, indirectly, the conceptual approach and analysis in AM1 and AM2 suggest that incremental innovation development requires especially applicable knowledge creation. In other words, incremental innovating requires people with application skills. They can either be research-trained employees of the company, or hired or collaborating researchers from universities or other research institutes. In these instances, the practical relevance of scientific skills is likely to be determined by the aims and product lines of the company. The arguments and indicators in the study of Jensen et al. (2007) seem to be assuming that innovation development is of this nature.

However, if the knowledge that moves between scientific research and industrial development relates merely to the operationalizing of an existing instrumental principle in a specific context, it may hold little potential for contributing to the advancement of science. Therefore, the researchers contributing to rapidly moving research fronts might not have the incentive to participate in such projects. This should be taken into account when considering the potential means to stimulate regional STI/DUI connections (Asheim 2012; Jensen et al. 2007). It can be doubted whether harnessing a region's scientific knowledge production system into the solving of very context-specific problems would benefit the region in the long run. Rather, based on the analysis of AM2 it can be tentatively proposed that the best STI/DUI connections present public research with such stimulating practical problems that they must be attacked using multiple research dispositions over longer periods of time.

Manniche (2012) has suggested that the differentiated knowledge bases approach should be complemented with an analytical distinction between exploration, examination and exploitation (rather than with the STI/DUI connection). As no empirical research along the lines suggested by Manniche has been published yet, and the approach developed in AM1 has only been operationalized once (in AM2), the two approaches cannot as yet be easily compared. However, the nearly simultaneous emergence of two alternative approaches for overcoming the lack of dynamism in the original differentiated knowledge bases approach demonstrates the topicality of this venture. More efforts are needed to make progress at this important research front.

To sum up the results, it should be pointed out that despite sharing with the Mode 2 argument (Gibbons et al. 1994; Nowotny et al. 2001) the view that universities should not and cannot shun the pursuit of the practical relevance of scientific knowledge, the results of the present thesis display important differences. One of the core Mode 2 claims is that as the context of application enters the processes of knowledge production, the boundaries between different knowledge-producing institutions begin eroding (Gibbons et al. 1994). The findings of the present thesis indicate that universities can and should retain their distinct ethos of academic and disciplinary ambition, while tolerating the pursuing of *phronetic* aims and related efforts to work around disciplinary boundaries (this flexibility need not exist without limitations, however). The findings of Wikgren-Kristoferson et al. (2011) support this view: the scientists most involved in disseminating their results to practical uses and public knowledge also perform best scientifically and carefully preserve their academic identities. The view that the societal engagement of academics is compatible with and largely driven by academic ambition is supported by many other studies (D'Este and Perkmann 2011; Feldman 2000; Franzoni and Lissoni 2009; Hayter 2011). As Wikgren-Kristoferson et al. (2011, 491) note, "excellent research is the base for effective diffusion, not *vice versa*".

The defenders of the Mode 2 argument are nevertheless correct in stating that the tension between scientific, disciplinary excellence and research whose relevance is determined by its practical value cannot be fully reconciled (Nowotny et al. 2001, 89, 91-95). Whereas they argue that the current development builds an escalating pressure upon the university (with an implication that the transformation of the university is unavoidable in the future), the research in the present thesis, however, presents the lack of full reconciliation as a productive tension. Working out this tension through the different processes that take place in different contexts and at different times is what keeps the university in a state of change. The university as an institution or organization is not a monolith that would abruptly undo its institutional structure. It adapts, and while doing so, seems to preserve its distinct identity.

5 CONCLUDING DISCUSSION

How does the practical relevance of scientific knowledge emerge? This main research question of the thesis has been addressed through the four sub-questions of the individual studies, and the results have been discussed with respect to analyses of the role of universities and scientific research in regional development. The findings show that the practical relevance of scientific knowledge differs by the context in which it is approached.

In a regional context where the universities have not been distinctly entrepreneurial, at least in Finland, the practical relevance of scientific knowledge is an assumption that may rhetorically prevail in policy documents concerning the “national innovation system”. In practice, however, this interpretation is pushed forward by local self-organizing networks. In other geographical contexts, the construction of practical relevance may have different origins. For example in state-led science city projects (Castells and Hall 1994), regional stakeholders might have little influence on the way that the role of public science is defined—yet, the actual processes in which the science-technology linkages are forged always take place in specific, physical locations. If the regional actors are not committed to the aim of seeking the practical relevance of scientific knowledge through an inclusive planning process, it may be more difficult to involve them later. Such dynamics have been shown to be at play also in the “construction of regional entrepreneurial advantage” (Feldman and Lowe 2011), when regional (self-)regulation of ethically sensitive research at the science-technology nexus is exercised. Inclusion and exclusion of different stakeholders from the regional planning processes can illuminate the potential of some regions to benefit from scientific research in their industrial development.

In the context of the innovation process, the practical relevance of scientific knowledge was shown to relate to both technological functionality and market functionality, and the latter was shown to have further aspects of user relevance and industrial relevance. Here, the emergence of the practical relevance of knowledge and knowledge-based innovation may be hindered by various discontinuities. This finding, when brought to the regional context, suggests that the management of discontinuities is a topic that deserves more attention. In this regard, there are two separate strands of research that could fruitfully complement each other: the research on sustainability transitions and the research on the role of various types of proximity in knowledge creation and innovation. Nooteboom's (2000) treatment of the various ways to bridge cognitive distance appears to be a promising approach for further studies on how conceptual discontinuity, as discussed in this thesis, might be solved in radical innovation development projects. The research on the various other dimensions of proximity (variously distinguished e.g. by Torre and Gilly 2000; Boschma 2005, such as organizational, social, technological and institutional proximity) seems to offer an interesting set of concepts to be considered in regard to potential discontinuities with respect to the various (technological, cultural, industrial, regulatory etc.) socio-technical elements involved. The conceptual and cognitive issues are not independent of these socio-technical elements, indicating that also other than cognitive factors influence the way in which the relevance and credibility of radical innovation projects emerge. This raises two questions.

- First, to which extent could the need for cognitive proximity or cognitive bridging be substituted with the other forms of proximity in meeting the challenges inherent to science-based *radical* innovation development in particular, in certain regional contexts?
- Second, how is this related to the way that the actors connect the local and broader geographical scales as they struggle to develop niches for radical technologies in the context of their respective socio-technical regimes (Coenen et al. 2012)? Further case studies of radical innovation projects in differently endowed regions would be needed to enable comparison between various geographical and regime contexts, in order to understand when, where and why new science-based developments emerge, and what role the "home" region plays in enabling these developments. A very topical issue is also where and why the eventual economic influences of new knowledge actually take place. This issue is of crucial importance to non-metropolitan regions such as Turku (the empirical context of the present thesis), which cannot be considered as a major player in the global scale, yet holds some potential for science-based innovating and new knowledge production.

In the context of scientific research, practical relevance—in cases where science-based radical innovations emerged—was shown to be gradually built into it rather than being discovered and translated from the research findings afterwards. This finding can be linked back to the discussion on entrepreneurial universities. Etzkowitz and Klofsten (2005, see Section 2.1) suggest that universities should develop an orientation for seeking out both the practical and the theoretical implications of the knowledge produced in them. Based on the findings of AM2, it seems that Etzkowitz and Klofsten (2005) have, on the one hand, hit the nail on the head: in the long term, knowledge production cannot remain both academically and practically valuable unless it is also theoretically ambitious. On the other hand, the suggested means of the entrepreneurial education of university students may be misplaced if this education is only about business management, organizing, marketing and finance. It would be important to expose university students to the various important practical problems that pertain to their scientific fields, and inspire them to come up with and analyze further problems that could become "their" problems in certain conditions. Without the results and ideas arising from these kinds of reflections, there will be little practically relevant substance to be managed and financed with the entrepreneurial mindset. The point here is, thus, not to say that regions might not need entrepreneurial infrastructure or education. Rather, the point is that only sparse attention has been paid to the *content* of the university knowledge, which is supposed to be an important fuel for the innovation system in regions that aspire to upgrade their industries in a more science-based direction.

If the regional environment is thought of as a systemic structure with different types of actors, the solution for stimulating the creation of practical knowledge seems to be to intensify the interaction between the actors in the regional industries and research—the knowledge-generating and knowledge-exploiting subsystems (Cooke 2002). However, the results of the two article manuscripts (AM1 and AM2) in the present thesis indicate that it is possible to focus directly on the *types of knowledge* moving through the linkages between the two subsystems. Further, the results imply that intensifying the university-industry linkages may not be the only way to inspire theoretically ambitious practical reflections. While the researchers whose activities were analyzed in the final study were quite self-educated in this regard, universities could also offer courses that incorporate elements that stimulate the combining of practical relevance with theoretical and methodological ambition for the larger cohorts of pre- and post-graduate students. Further, the researchers studied in AM2 also found support or at least tolerance for seeking their own research direction from important academic seniors (this aspect of the cases is further analyzed in Höyssä 2012). Cultivating and supporting these types of ambitions does not require costly changes in the regional or national innovation system structures. Rather, such ambitions can be advanced within universities and are compatible with all the three university missions of achieving high quality, that is, with regard to research, education and interaction with the society.

Table 5 illustrates how some of the findings of the individual articles and manuscripts relate to each other and what are the related spatial questions. Part of the analytical framework employed in A2 is used as the organizing principle of Table 5, as its first column on the left, in order to open up the different levels in which novel technologies can be analyzed.

Table 5 Some cross-cutting themes in the thesis.

Level of analysis	***Relevant knowledge types***	***Potential discontinuities***	***Spatial questions***
Instrumental principles	Instrumental (high degree of novelty)	Conceptual discontinuity	Where is the new knowledge created? Where is it understood and the opportunity grasped?
New components / methods	Instrumental & applicable (high degree of novelty)	Technological discontinuity	Where is the skill to put the principle to practice?
Product subsystems	Applicable (new combinations of existing instrumental knowledge)	Technological discontinuity	Where is there a need for new technology and the skills to use it?
Product	Applicable (new combinations of existing instrumental knowledge)	Market discontinuity	Where is there a need for new products?
User practice		Market & cultural discontinuity	Where do the lead users and potential early adopters emerge?
Regime / sector	Complicit competence to support discontinuity management	Market, industrial, technological, policy, regulation, disciplinary, conceptual and cultural discontinuities	Where is there a niche for new socio-technical experiment? What kind of place and policy would be needed for overcoming the discontinuities?

Table 5 summarizes how scientific knowledge relates to technological development and which types of discontinuities may hinder this development. The top row shows that instrumental knowledge—a new invention—may be conceptually discontinuous. The rows below that show that the discontinuities potentially involved may become more and more varied as the science-based technology emerges and is implemented into respective products and as these products seek their respective market. Because knowledge creation and the overcoming of the potential discontinuities always take place in specific geographical contexts, the present thesis opens up a range of spatial questions from a slightly new angle, calling for attention to the spatial issues that are related to the emergence of novelty. Some of these issues are summarized in the fourth column of Table 5.

The present thesis has made some headway in illuminating both how science is able to find novel solutions and why progress tends to be slow and uncertain, and how it may be related to the spatial structures of knowledge production in specific local or regional environments. This thesis has sought to discuss these themes from a regional perspective and identified several bodies of research that might interestingly complement or be complemented with the findings and approaches of this thesis. Yet, future research needs to work out the mechanisms through which the useful knowledge can eventually come to serve regional economic development and well-being in the region of its origin and beyond. To accomplish this, it would be important to explore further the possibilities to fit together the actor-oriented approaches presented in this thesis and approaches that are explicitly developed for analysis at the regional level—in particular the differentiated industrial knowledge bases approach (Asheim 2007; Asheim and Gertler 2005). Thus we could even inch closer to understanding how regional development, scientific research and the solving of present problems introduced by climate change, food safety, the escalating costs of health care, and the need for affordable energy, among other things, can be productively related.

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I

The co-evolution of social and physical infrastructure for biotechnology innovation in Turku, Finland

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Abstract

We studied the emergence of biotechnology in Turku, Finland. First, we analysed it as a result of the interaction between the city and its national and international environment, focusing on the city's industrial policy as the mediator. Second, we diagnosed the construction of BioCity, the first biotechnology centre building of Turku, as a key event: the conceptualisation and construction of BioCity required a new kind of collaboration between the city administration, the universities and various commercial actors. We argue that the systems approach to regional development needs to be complemented with approaches that focus on the regional mechanisms of adaptation.

Keywords: Regional change; Science park; Science and technology policy; Network of mutual empowerment

1. Introduction

According to some contemporary theories of regional development, regional performance should be understood in systemic terms, resulting from interaction between the region and its environment (Vet, 1993; Cooke and Morgan, 2000/1998). Others, however, have emphasised that regional development is path dependent, with certain events being more influential on the development trajectory than others (Sotarauta and Bruun, 2002). In this article, we apply both perspectives in the case of the city of Turku, Finland. While small in international comparison, Turku hosts a significant concentration of Finnish bioindustry, particularly in the areas of pharmaceuticals and diagnostics. On the one hand, we analyse the emergence of biotechnology in Turku as a result of the interaction between the city and its national and international environment. We focus particularly on the city's industrial policy as the mediating factor. On the other hand, we focus on one of the key events in the biotechnology trajectory of Turku: the construction of BioCity, the first biotechnology centre building in the city. We argue that this event was of key importance for making Turku the centre for biotechnology that it is today, not only because it introduced the biotechnology centre as an innovative environment for research and development, but also because the conceptualisation and construction of the biocentre building required a new kind of collaboration between the city administration, the universities and various commercial actors. This collaboration very much characterises the Turku style of making biotechnology.

More generally, we argue that the systems approach to regional development, which emphasises regional

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adaptation to changes in the external environment, needs to be complemented with approaches that focus on the mechanisms of adaptation. We propose that differences in regional performance are equally dependent on the mechanisms through which regions channel the pressures from the environment as they are on the components of the region as a system, such as resources, institutions, policies, etc. With "mechanisms" we understand the processes through which change is initiated and implemented in the region. When moving to this level of analysis things tend to become messy, because the connections between the processes that function as "mechanisms," and the environmental pressures that a system level analysis detects, are seldom direct in the sense of being mediated in a transparent way. The mechanism attended to in this study, the building of BioCity, is a good example of this. The building of BioCity can be seen as one of the mechanisms of regional adaptation. However, the project was not initiated as a result of deep insights in the dynamics of regional economy. Instead, it was born as a reaction to the threat of not getting access to national funds that were distributed to regional biotechnology centres at the end of the 1980s. The immediate cause of the BioCity process was thus the fear of being deprived of specific resources, which had little to do with the problem of regional development as a whole.

Studying the mechanisms of regional adaptation is different from studying systems, because the system level analysis explains only the function, not its causes. When the mechanisms are processes of social interaction, as in the BioCity case, they must be studied as such. Applying this approach, we discovered that the potency of BioCity as a "mechanism" lay in the new culture of collaboration that the construction of the centre initiated. This, again, was very much connected to the fact that BioCity was conceptualised as a boundary object—an idea with which several actors could identify, despite their heterogeneity. The problem with boundary objects is that they are under constant threat of disintegration. In the BioCity case, such a fate was avoided due to the strong but flexible institutional networks that were built to anchor the concept. These networks turned out to be durable. They form the foundation of the present-day collaboration in Turku. The results of the present study lead us to hypothesise that more detailed studies of other science parks and technology centres may reveal regional effects that go beyond them being just "innovative environments."

This research is based on forty interviews with local and national policy makers, researchers at the universities in Turku, university administrators, business people and many other key individuals in Turku. The interviews were carried out in two waves in 2000–2002. The interviewees were selected on the basis of information that was gained through documents and previous interviews. Most interviewees have actively participated in the process described below. In addition to the interviews, we have used large amounts of published and unpublished material, such as minutes of project meetings, strategy documents and evaluations.

In what follows, we offer a bifocal perspective on the evolution of the Turku biotechnology centre. After a glance at the Turku biotechnology setting, we begin the story with an account of the systems of innovation underlying the evolution of biotechnology in the region. We then continue by detailing the social processes and contingencies that maintained the trajectory of development. We conclude with reflections on the significance of innovation systems and social processes, respectively, on the emergence of new technologies.

2. The setting

Turku is Finland's fifth largest city (population 172,000), located in south-western Finland by the Baltic Sea. There are at least 35 biotechnology companies in the region, representing 28% of Finnish and nearly 2% of European bioindustry (measured in the number of companies). In addition to actual biotechnology companies, a number of service-providers have emerged.[1] Most of the companies are rather small, but the bio-cluster also includes R&D oriented subsidiaries of a few larger companies and multinationals, such as Orion Pharma, Schering and

[1] The number of biotechnology companies is from the database of the Research Institute of the Finnish Economy; private communication by Terttu Luukkonen. According to the local umbrella organisation Turku Bio Valley Ltd. there is more than 60 bio-related companies in the Turku region. The latter figure includes also service companies (such as computing, consulting and statistical services for drug development firms) that are not doing actual biotechnology development.

Perkin-Elmer. Local biotechnology-related research and business is estimated to employ approximately 3500 people.

Turku is relatively strong also in the academic domain. The two universities and the polytechnic schools of Turku offer educational programmes in chemistry and life sciences for more than 800 new students a year (Working Group for Research and Education, 2000; Nordic Adviser Group, 2000). The universities participate in seven Graduate Schools[2] in the life science area, employing more than 150 graduate students from the city in 4-year positions (Working Group for Research and Education, 2000). In 2002, the Turku universities accounted for more than 16% of all Finnish doctoral degrees in the natural and medical sciences (KOTA Database, 2003).

In a recent, international evaluation of Finnish biotechnology environments, Turku was described as being "notable for a strong commitment to biotechnology, which dates back 15 years, involves all interested parties (universities, industry, city government) and is said to be their top priority" (Academy of Finland, 2002, pp. 72–73). According to the panel, "[c]onsiderable thought, effort and investment have gone into an ambitious integrated programme for biotechnology development (···) [Turku] has set as its aim to become an internationally recognised centre of biotechnology in Finland and Europe". The evaluation panel recognised the following strengths in favour of this aim: quality of the universities, commitment of the city government, strong presence of pharmaceutical and diagnostics industry, strong collaborative spirit, compact campus and openness to multiculturalism (Academy of Finland, 2002). Who, then, should get the credit for this promising state of affairs?

3. Regional change as adaptation

3.1. Regional policy-making: surviving in international competition

There exists a vast literature on the general forces behind regional attempts to revitalise their industrial policies (Braczyk et al., 1998; Cooke et al., 2000; Cooke and Morgan, 2000/1998; Dalum et al., 1999; Isaksen, 1997; Kostiainen and Sotarauta, 2000; Saxenian, 1994; Sotarauta, 1999). According to this body of research, contemporary industrial policies, in both regions and nations, are increasingly driven by the need to adapt to economic globalisation. The background is that many states have moved from redistributive regional policies to promoting successful regions, and that the opening of international markets has exposed local economies to international competition (Vet, 1993; Cooke and Morgan, 2000/1998). Thus, regions are more dependent than before on the international competitiveness of their own industry, at the same time as the demands on that industry have increased drastically. Reduction of production costs is no longer sufficient for competitiveness, but must be supplemented, or even substituted, by "continuously increasing product quality, timeliness of service, flexibility, rapid and continuous innovation, and command of strategic technologies"(Vet, 1993, p. 98).

Contrary to what some might have expected, globalisation does not level economic space—regional specialisation and strategic localisation are important ingredients of the new economy. De Vet (1993), for instance, has argued that the internationalisation of markets reconfigures the international division of labour, encouraging regional specialisation. The reason for this is, according to him and many others, that the competitiveness of companies is not only dependent on what happens within them, but also on the environment in which they operate (Edquist, 1997; Lundvall, 1995/1992; Nelson, 1993; Schienstock, 1999). Good transportation and communication infrastructures, competent labour force and the reliability of supporting companies are examples of performance enhancing features of the operational environment. The list can be extended, and notions such as "regional innovation systems" and "regional innovation milieus" have been used in reference to the set of regional elements that positively affect the competitiveness of firms (for a review of the concepts, see Kostiainen, 2000). A most important point is, however, that different economic activities require different kinds of supporting environments (Tidd et al., 2001), which means that regions with limited resources must make choices (Cohendet and Meyer-Krahmer, 2001). In practice regions should focus on "specific rather than on general industry needs"(Vet, 1993, p. 17).

[2] The Graduate Schools are a part of the national system of higher education. They are administered by MoE.

3.2. Boosting biotechnology in Turku

Turku is the oldest city in Finland and has, as a former capital, played a significant political, economic and cultural role in the history of Finland. In modern times, however, Turku has been bypassed in national significance by the Helsinki area and, more recently, run into considerable competition with other regional centres, such as Tampere, Oulu and Kuopio. From a cluster-perspective, the Turku region has five strong "groupings": the metal group, the real estate group, the logistics group, the graphic industry and the biotechnology and food group, which is structured around research-intensive pharmaceutical and diagnostics industry, as well as more conventional food processing (Stenholm, 2000). What is striking is that the Turku region has a weak position in two of Finland's most important national clusters, the forest cluster and the telecommunications cluster. This is an important background for understanding the strength of the region in the life science sector.

The development of the biotechnology trajectory in the Turku area was preceded by an economic downturn. The region suffered a considerable decline in employment during the recession of the Finnish economy in 1990–1994. Turku was particularly struck by the sudden end to trade with Russia, which led to a closedown of most of the textile, clothing and shoe industries and approximately 40% of the food industry. The latter was also affected by the Finnish membership in the European Union. The recession affected the political climate in the whole country (Schienstock and Hämäläinen, 2001). The need for targeting industrial policies was generally acknowledged, and cities and regions started making strategic plans for the future. According to deputy mayor[3] Juhani Määttä, 1992–1996 was a period of conflicts. There was an awareness of "Turku being bypassed by Oulu, Tampere and Jyväskylä".

The first regional policy institution to react to this situation was the Regional Council of Southwest Finland, which in 1994 established a regional Centre of Expertise (CoE) in the Turku area. This was part of a national programme for such centres, which had been launched earlier that year. The idea was to encourage the definition and development of regional core capabilities through collaboration between different kinds of actors, such as local industries and universities (Laaksonen, 1994). The Regional Council of Southwest Finland selected biotechnology, materials research and information technology as the main focus areas. The rationale for investing in biotechnology was, on the one hand, that the region already had a strong research base in the two local universities and, on the other, that the major players in the Finnish pharmaceutical, diagnostic and food industry were situated in Turku. The local CoE programme was designed to complement the existing research base by building a system for adding value to biotechnological innovations (Regional Council of Southwest Finland, 1994).

The city of Turku reacted somewhat slower. This might sound surprising considering that the city had participated in the establishment of a local technology centre since the end of the 1980s by investing millions of Finnish marks[4] in facilities and equipment. However, it had operated more as a partner than as an initiator (Höyssä, 2001). Pro-active policy started only in 1997, when the first Turku strategy was formulated and accepted by the city council. The strategy identified biotechnology, information technology and culture as strategically significant areas, and emphasised the need to encourage knowledge production, innovation and the emergence of new technology firms (Turku City Council, 1997). This represented a major shift in attitude, because previously these activities had primarily been seen as concerns of the universities and industry, not of the city administration.

In 1999, the city decided to invest 12.6 M € in *Turku Bio Valley Ltd.*, a company that would own, manage and arrange production facilities for bio-companies. This company has been the main vehicle for the city's biotechnology policies. Among other things, it mobilised the universities and the local industry to formulate a common strategy for biotechnology development in Turku. In 2001, the City Board of Turku restructured the technology centre, which at that time was restricted to five technology centre buildings, into a larger entity, Turku Science Park,

[3] In Finland "mayor" refers to an administrative position, "city manager".

[4] Euros were introduced to Finland in the beginning of 2002. The amounts of Finnish marks prior to that are converted with the 2002 value, € = FIM 5.94.

which includes all relevant R&D activities in the city, regardless of their specific location. The core fields of the science park are biotechnology and information and communication technology (ICT).

The economic expectations on these two fields are high in Turku. While small in international comparison, Turku hosts a significant concentration of Finnish bioindustry, particularly in the areas of pharmaceuticals and diagnostics. Since the birth of the technology centre and the more recent science park a number of small biotechnology firms have appeared on the side of traditional pharmaceutical companies. At the moment (end of 2002) there are 63 bio-related companies in the Turku region, among them 9 operating in the field of pharmaceutical product development, 15 in diagnostics and products needed in biotechnological research, 5 in functional foods, 4 in biomaterials, 8 in instrumentation and equipment, 9 in research-services and 10 in business and innovation services for biotechnology companies. The R&D personnel of these enterprises amounted to approximately 700 in 2000 (Working Group for Research and Education, 2000). In some fields (biomedicine, diagnostics and biomaterials), the city hosts almost 40% of Finnish start-up companies[5] (Kuusi, 2001).

The number of people employed by the biotechnology cluster in Turku has been estimated to be almost 3500 (university researchers included).[6] According to targets set during strategy work led by city-owned Turku Bio Valley, the grouping should employ up to 10,000 people in 2010 (Nordic Adviser Group, 2000). Most of the interviewees of the present study considered this to be a realistic target. It should be noted, however, that the interviews were made before the present economic downturn. In 1997, the software and electronics grouping in the Turku sub-region employed approximately 1700 people. Here, visionaries have talked about 5000–8000 new workplaces in the region of Southwest Finland within the period of 2000–2005, a substantial part of which could come to Turku (Carlsson, 2000). Thus, all in all the two “clusters” are expected to produce 10,000–13,000 new workplaces in Turku within this decade. This can be compared with the numbers of 23,200 jobs lost in the Turku sub-region in 1990–1993 and 20,100 new jobs created in 1993–1999 (Statistics Finland).

3.3. National science and technology policy

The developments in Turku—both the growth of local biotechnology-related research and industry and the policies of the local authorities—interacted strongly with processes at more general, national and international, levels. Changes in the national science and technology structures were of particular importance. This series of events can be traced back to the late 1970s, when the existing technology policy was criticised for being bureaucratic, inefficient and not being able to target technological development. There were concerns that Finland would not be able to keep up with the accelerating rate of technological change, particularly in the field of microelectronics. A few years later, Finnish technology policy was reformulated, making *targeting* an important principle of funding. The idea of national technology programmes was conceived and a new institution, the National Technology Agency (Tekes), was set up in 1983 for its implementation (Vuori and Vuorinen, 1994). These changes were of great importance for Finnish biotechnology, because they allowed targeted economic support to new fields of research. One of the first national technology programmes, the Gene Technology Program (1984–1987), was devoted to biotechnology. The new technology policy also ensured a quantitative increase in Finnish R&D (Lemola, 2001). Thus, Finnish R&D investments (measured as percentage of gross national product (GNP)) increased faster than in most other OECD countries in 1985–1991.[7]

Another key institution at the national level is the Academy of Finland, one of the main agents of Finnish *science policy*. The Academy, which in effect is a national research council, participates in the planning and funding of research programmes and funds researchers and research teams at universities. In addition, it evaluates the state and standard of Finnish

[5] Research-intensive companies that are less than 5 years old.

[6] The source of this estimate is Turku Bio Valley, the cluster company for biotechnology at the Turku Science Park.

[7] However, it should be noted that Finland started from a very low position (just above 1.5%) in 1985 (compare with, for instance, Japan, Sweden, the US, and Germany whose R&D investments were around 2.7–2.8% of GNP in 1985). The long-term significance of the technology policy initiated in the 1980s can be seen in the increase of Finnish R&D input from approximately 1.5% in 1985 to 3.0% in 1998. During these years Finland passed all countries but Sweden in R&D input (as share of GNP).

science and provides expertise in science-policy issues (Kuusi, 2000). The Academy operates under the Ministry of Education (MoE). Since 1988, biotechnology has been one of the main fields of support by MoE and the Academy. A series of sequential research programmes in molecular biology and biotechnology have spanned to the present. The programmes provided financial support to the four strongest biotechnology research concentrations of Finland: Helsinki, Oulu, Kuopio and Turku. For instance, in 1988–1995, MoE allocated EUR 76.2 m to biotechnology (Academy of Finland, 1997, p. 93), mainly by supporting the universities of these four cities. The radically increased flow of money has been crucial for boosting Finnish biotechnology and making it internationally competitive (Abbott, 1997; see also Academy of Finland, 1997; Academy of Finland, 2002). Turku was one of the cities that were able to benefit from these developments.

In sum then, an analysis from a systems perspective suggests that the biotechnology trajectory in Turku is the result of external pressures on the local economy and insightful local and national policies, which have allowed the city to be pro-active. Through investments in the biotechnology sector, the city of Turku has tried to restructure its economy, with an emphasis on high technology sectors with good growth prospects for the future. The favourable developments do not result from policy alone. The major players are, quite naturally, the universities and the corporations doing the research and developing the products. However, the concerted action of national and local authorities has accelerated the growth of these activities significantly.

4. Constructivist perspective on regional change

4.1. Regional dynamics revealed through a case study

In this section, we want to deepen, and partly modify, the system-level explanation of the evolution of biotechnology in Turku. A strong trajectory has indeed formed in Turku. But it would be misleading to say that visionary political authorities created it alone. The CoE programme of 1994 mentioned in Section 3.2 did not emerge out of the blue, but explicitly drew on an already existing culture of collaboration between people and organisations involved in biotechnology (Regional Council of Southwest Finland, 1994). Indeed, as the international evaluation panel of biotechnology stated, the regional "strong commitment to biotechnology" in Turku dates back 15 years. We argue that this is how much we should go back in time to explain how biotechnology and the development of the science park even became options for the regional policy-makers. In our empirical study, we searched for the origins of the collaborative spirit.

Collaborative spirit seems to be an important ingredient in phenomena such as *innovative milieu* (Castells and Hall, 2000/1994; Castells, 2000), *associational capacity* (Cooke and Morgan, 2000/1998) and "collaborative practises" (Saxenian, 1994), which have been identified as the sources of regional competitiveness in high technology. Guy (1996) notes that science park initiatives always involve several parties and many interpretations of the park's aims. It seemed to us that the process of aligning these interests must be informative from the perspective of co-operation and regional capacity to change. We set out to study this process in Turku. We did not focus on the current science park development, but took as our starting point the developments that produced the very first "technology centre" buildings in Turku. We claim that the local culture of inter-organisational and inter-personal collaboration within biotechnology in Turku has its origin in the process of building the BioCity biocentre. This project was also a significant catalyst for the subsequent rapid development of local research and business in the field. Note that we are talking about the *process* of planning and building the BioCity, not about the building as such or even the collaboration occurring within the building after it had been built.

BioCity, which was built in 1989–1992, is a so-called technology centre building that houses both academic research and SMEs. It gave the local bio-research a face—an identity that has been of great external as well as internal significance. The regional and local governments' role in the process was at first marginal and participation was based on the idea of being a partner rather than on any ambitions to initiate collaboration. In Section 6 we will consider what this means from the point of view of regional capacity for change.

Today, the seven floors of the BioCity building (gross surface area 37,000 m^2) host fourteen research units from two of the city's three universities

(University of Turku and Åbo Akademi University), twelve companies in the fields of pharmaceuticals and diagnostics, the regional office of the Finnish Medical Society Duodecim, a congress centre, a laboratory equipment store, companies selling communication technology equipment and services, a bio-science library, a restaurant and cafeteria, a grocery store, a kiosk and an information office. The largest research institutions are the Centre for Biotechnology, established jointly by the two participating universities and the University of Turku Medical Faculty's MediCity laboratory. BioCity is situated next to a group of similar technology centre buildings (DataCity, ElectroCity, EuroCity, PharmaCity) that have been built during the last 15 years. The term technology centre is in this text taken to signify a smaller scale science park, consisting of one or a few buildings in which interaction between organisations (sometimes companies only, sometimes also university) is encouraged. Often there is a technology centre organisation, which has responsibility for the development of the centre.

Yet BioCity is more than a building. It is also a range of ideas, and in what follows we outline the process through which these ideas materialised into a building bristling with activity. We focus on BioCity as a socially constructed artefact. Knowledge about the kinds of interests that were actually built into the project helps to explain the potential of, and tensions in, the outcome. In Section 5, a networking perspective is applied in order to explain why the BioCity project could be sustained, despite of the diverging impulses. Taken together, the constructivist and networking analyses show that the significance of the BioCity building was not only to constitute an R&D facility or an "innovative milieu", but perhaps more importantly—from the perspective of long-term development of local biotechnology—to necessitate a complex negotiation process involving a multitude of actors to get it up and running.

4.2. Gathering the actors

In the middle of the 1980s, the biotechnology-related institutions in Turku consisted of two universities and a few medium-sized (though large in the Finnish context) companies. Turku had 30 ongoing research projects in 1986. This positioned the city as Finland's second largest centre in the field, surpassed only by Helsinki, which dominated the field with its 126 projects. In Turku, the University of Turku and the Åbo Akademi University pursued biotechnology-related research in several departments. At the University of Turku, for instance, the departments of biochemistry, chemistry, biology, biomedicine, clinical theory and dentistry performed such research.

In the commercial sector, biotechnology was primarily used by medium-sized companies. Turku had a particularly significant concentration of enterprises related to health care and food processing. Almost half of the national pharmaceutical industry (Farmos-Group, Huhtamäki), over half of the national diagnostics industry (Wallac, Farmos-Group) and approximately half of the national food industry (out of which Huhtamäki, Hartwall and Suomen Sokeri had interests in biotechnology) were situated in the Turku region. Some of these companies were engaged in co-operation with academic research—a form of collaboration quite uncommon in Finland at the time. Both Farmos and Wallac had had common research projects with the University of Turku since the 1970s in fields such as diagnostics. In 1988, Farmos, Huhtamäki and Wallac entered a national project on protein research. At the same time, to mention another example, the Department of biochemistry (University of Turku) co-operated with the industry on diagnostics, protein and enzyme technology and the development of various biotechnological methods.

At this time a particularly important framework for collaboration emerged. A project called the Southwest Finland Biotechnology Development Project (SWB) was initiated in 1987 by the two old friends, Pekka Mäntsälä, professor at the Department of Biochemistry, and Heimo Välimäki, co-ordinator at the University of Turku Centre for Extension Studies. They envisioned a project that would strengthen biotechnological research in the region. Mäntsälä utilised his relations to local companies and Välimäki his contacts within the public sector to enrol the University of Turku, the Åbo Akademi University, the Provincial government, the city of Turku and regional companies that were utilising biotechnology. SWB grew into a joint discussion forum for the local biotechnology actors. The existing co-operation projects were an essential foundation that enabled the local actors to see potential value in the search for common advantages in biotechnology.

SWB had a formal position in the local “innovation system” through the participating officials and funding from the Provincial government. As a result, the project conceptualised biotechnological research primarily as a regional interest. To further its aims, the project gathered a set of heterogeneous, local and regional actors into a biotechnology forum. Although SWB was not always successful, its sub-projects anticipated BioCity through their emphasis on boundary-crossing collaboration and synergy as a means for acquiring resources for biotechnological research in Turku. Such sub-projects included, for instance, persuading the Technical Research Centre of Finland (VTT) to start a regional laboratory in Turku and providing local extension education and training in biotechnology. Even if SWB failed with VTT (not until 2002 did VTT establish a unit in Turku whereas SWB was only a 3-year project), SWB had an important educational function in the development of local biotechnology. Some of those who later were to become leading researchers in Turku, participated in the first courses arranged by SWB.

Another important local development was the adoption of the science park concept from countries like Britain and the United States (Vuorinen et al., 1989). In Turku, the idea was first tried out with the construction of DataCity, a facility for research and development in information technology, electronics and business administration. DataCity, built in 1988–1989, was the first in a series of technology centre buildings that are still being planned and built in Turku. Today, the technology centre strategy is affirmed and promoted by local and regional authorities, who even have taken it upon themselves to co-ordinate the development (Bruun, in press). However, at the end of the 1980s there was no such involvement, and DataCity was pretty much the product of visionary and resourceful individuals. Juhani Lundén, a construction entrepreneur, took the first step. Even though Lundén’s intention was to do real estate business, he designed the scheme with people active in other fields. These other persons were Erkki Soini, research director at Wallac, Jussi Kaisti, chief executive of the Adax advertising agency, Juhani Leppä, manager at the KOP bank, Timo Järvi, professor of computer science at the University of Turku and Christer Carlsson, professor of business administration at the Åbo Akademi University. Lundén and Kaisti suggested that a Foundation for New Technology (FNT) should be established to enrol new actors in the DataCity-project. FNT, originally envisioned by a construction entrepreneur and an advertising director, was to become the main agent in planning and realising BioCity.

FNT promoted the technology centre concept for new technologies. Its interpretation of technology centres was that of *synergy* between academic and industrial participants—a concept developed and promoted especially by business management professor Carlsson. Synergy was to be effected by gathering an optimal community of researchers, doctoral students, theoretical knowledge, technical resources and appropriate research problems to be solved by the community; and synergy was to be catalysed through the physical arrangements of the centres that would enable and encourage interaction. It was envisioned that the private companies could benefit from this synergy for instance by bringing their own problems into the focus of research.[8] The idea is similar to the idea of “innovative milieu” promoted in much of the science park literature (Castells and Hall, 2000/1994; Castells, 2000; Ferguson, 1995). FNT organised meetings, seminars and get-togethers, the purpose of which was to mobilise support for its visions. At the time, synergy was experienced as a fresh and exiting concept, and FNT was rather successful in enrolling a widening circle of supporters. It attracted not only researchers and business people, but also influential local politicians and officials from national ministries. In contrast to SWB, FNT had no formal position in the local innovation system: its influence was based solely on the authority of its members. In the beginning, it was funded primarily by donations from various companies, and the members had to put a lot of effort into raising the donations.

The process leading to the building of BioCity and to the formation of collaboration around technology centres was highly path dependent. This can be demonstrated through the role of DataCity. First of all, the team of individuals that later initiated BioCity was first gathered when DataCity was planned. DataCity was in a sense good training. BioCity was a much

[8] In DataCity, all obstacles of synergy—such as envy and competition—were to be avoided. For example, IBM was not allowed to move in, since it was a serious competitor to an older tenant, Nokia Data.

grander scheme, because biotechnology research required a lot more expensive research infrastructure than ICT. Without the team the idea of a synergistic technology centre would probably not have emerged in Turku as soon as it did. Second, the team created FNT, an organisation that successfully promoted the idea of collaboration in general and not just within the fields of information technology and electronics. Third, the success of DataCity, which was a privately funded technology centre, encouraged local and regional authorities to take more responsibility in similar projects in the future. Fourth, the success of DataCity was important in convincing national authorities, like MoE, that Turku had the capacity to implement such radical institutional innovations. Finally, to build DataCity, the idea of a technology centre had to be conceptualised and adapted to local circumstances. When the same people and organisation later continued with the BioCity project, they did this with a high degree of self-confidence from the beginning.

4.3. Technology centre as a boundary object

The idea of BioCity had been discussed since the building of DataCity. However, until the spring of 1988 both FNT and SWB had focused on smaller projects such as getting the VTT laboratory to Turku. The predominant belief within FNT and SWB was that it would take years before the situation in the region would be ripe for a biotechnology centre. The spark that actually ignited the BioCity process can be found in the changes of Finnish science and technology policy in the late 1980s (see Section 3.3). MoE was planning significant additional funding to biotechnology within the framework of the new policies. Four of the strongest universities in biotechnology were chosen as targets. In the autumn of 1987, a working group suggested that EUR 1.07 m should be distributed to the two Turku universities, EUR 1.07 m to Kuopio, EUR 1.27 m to Oulu and EUR 4.44 m to Helsinki. A major part (EUR 3.54 m) of the Helsinki money was reserved for establishing the Institute of Biotechnology at the University of Helsinki (Ministry of Education, 1987, pp. 26–28). The people involved in FNT and SWB in Turku reacted strongly against the proposed allocation. They thought that Turku had been done injustice considering the scale and state of local research in the field.

Turku biotechnology seemed to have a visibility problem. FNT and SWB people felt that the national actors were not informed about what was actually going on in the city. Thus, both FNT and SWB reacted by developing strategies to increase visibility. SWB decided to send a broad delegation to Helsinki to explain the regional need for biotechnology investments. It also intensified lobbying activities to persuade VTT to establish a protein research laboratory in Turku. FNT, on the other hand, reacted to the situation by initiating the BioCity process. The research director of Wallac, Erkki Soini, suggested at a FNT board meeting that FNT should take action to build BioCity to demonstrate that there is a strong clustering of biotechnology in Turku. FNT arranged a meeting for the rectors of the local universities, the city authorities and representatives of the bio-sciences. The meeting decided to establish a joint committee of University of Turku and Åbo Akademi University to further the BioCity project.

As the two-university committee started its work in May 1988, the initiative and the power to define the meaning of BioCity gradually moved from FNT and SWB to the universities. Since a research-intensive biotechnology centre without considerable participation by the universities was inconceivable, and since the primary objective was to make research in Turku competitive in the allocation of national funding of science, the basic research needs of the universities were given priority at this stage. The committee estimated that the two universities would need half of the space in BioCity. The Åbo Akademi University would move its departments of biochemistry and pharmacy and biology to the new building, while the University of Turku would move several research groups (but not whole departments) belonging to the Faculty of Mathematics and Natural Sciences and the Faculty of Medicine. The timetable was extremely pressed, and the report of the committee had to be presented to MoE before being analysed in light of the new action plans and economic plans of the universities.

At MoE, officials saw the BioCity-plans as superficial and unrealistic. The response was negative, which was serious since the universities needed the approval of MoE in order to continue with the project. The University of Turku established a new committee, the Havu Committee, to revise its plans in relation to BioCity—that is, to make them more "realistic". During the work of the Havu Committee, the BioCity-activists managed to convince Cristoffer Taxell, the Minister of Education, of the rationality of building a biotechnology centre in Turku. The BioCity project had, at this point, started to have the effect that its initiators desired, namely, to attract the attention and commitment of financiers at the national level.

Minister Taxell asked one of his trusted officials, Arvo Jäppinen, to ensure that the planning would take place in accordance with MoE's views. The Turku people welcomed Jäppinen's participation. He recommended that one more joint university committee should be gathered and that it should include also the mayor or deputy mayor of the city of Turku. As it happened, both of them had prior experience in technology centre issues in other contexts. The mayor, Juhani Leppä, had been one of the driving forces behind DataCity when working for the KOP bank, and the deputy mayor, Juhani Määttä, had been involved in establishing the internationally well-known technology centre activities in the Oulu region.

The task of the committee was to make final plans concerning university participation in BioCity. As a result of the different structure of the committee, the dominant interpretation of BioCity also changed. It was no longer seen primarily as a vehicle for getting access to national funding, but more as a project in its own right. MoE emphasised the need for consensus and compromise within academia and the need for getting outside funding, which necessitated keeping the industry involved as well as substantial financial support from the city of Turku. The negotiations resulted in a new, more complex notion of BioCity:

> "[BioCity's] primary objective is to advance research and to maintain its high international level; to strengthen the industry's R&D activities; and to promote the establishment of start-up companies. The concentration of activities and the integration of resources will provide for a (1) new organisation of research, (2) development of new research methods, (3) production and quick utilisation of new knowledge, (4) development of basic, post graduate and extension education, (5) deepened and broadened collaboration with national and international biotechnology centres and (6) development with the region's production structure and production operations in collaboration with the Province of Turku and Pori, the city of Turku and the local companies." (University of Turku and Åbo Akademi University, 1989, p. 7. Our translation.)

Different actors saw different virtues in the project. For the construction entrepreneur, BioCity never ceased to represent business; for industry, it was a chance to interact more easily with university research; for universities, it improved research facilities; and for the city representatives, it was a tool for economic transformation. As a result of constant negotiations between various committee members, a vision of the future biocentre emerged that was coherent enough to be acted upon. The vision gathered the different ambitions and needs in one concept: the BioCity. In the sociology of science, ideas that "inhabit several intersecting social worlds . . . and satisfy the informational requirements of each of them" have been called *boundary objects* (Star and Griesemer, 1989, p. 393).

BioCity fulfils the criteria for a boundary object; it was adopted by heterogeneous actors pursuing quite different activities and it satisfied the informational requirements that each of these had on the biocentre as a prospective future. Collaboration between the distinct social worlds was possible because the various interpretations reinforced each other, or at least did not contradict each other. For instance, the emphasis of national and local policy makers on industry involvement was not contradictory to the universities' objective to attract more research resources to the Turku area. In fact, the former could now be conceived as a prerequisite for the latter.

Returning to the key question of this section, "what is the source of the collaborative spirit among biotechnology developers (in a broad sense) in the region," we contend that that source is the fact that BioCity was constructed as a boundary object. As such it became a template for future development. All later institutions of collaboration—such as BioCity Turku, BioTurku and even the Turku Science Park—are derivatives of the BioCity concept.

5. Networking perspective

5.1. Creating empowerment

The construction of boundary objects requires that actors can be made to promote the object despite differences in interpretation. To explain how this is possible, we suggest that one needs to focus on the networking process through which actors are enrolled to the "common cause." Here, actor-network theory, or ANT, offers important insights (Callon, 1991, 1997/1995, 1997/1987, 1999; Latour, 1987, 1996/1993; Law, 1997/1987; Law and Callon, 1997/1992). In ANT, as we interpret it, networks are studied from the perspective of agency. An actor network is a dynamic set of relations between elements that empower some agent. In this view, actors acquire agency—capacity to act in certain ways—as a result of establishing relations between a network of other actors, things and processes.

We prefer to speak of *empowerment networks*—rather than actor networks—and to distinguish these from *interaction networks*, which are defined in terms of interaction rather than empowerment and agency. Interaction networks may or may not function as empowerment networks for some particular actor. The former is the case if the interaction network becomes a condition for that actor for performing some desired action. Thus the capacity of, for instance, a university department to perform research in an area where expensive equipment is needed, might be dependent on its membership in an interaction network that co-ordinates the use of equipment.

Recapitulating the course of events, FNT and SWB formed the original interaction network that initiated the construction of the boundary object called BioCity. This network was able to present BioCity as an obligatory passage point (Callon, 1986) through which everyone willing to get additional resources for biotechnology-related activities had to go. Universities were enrolled by the promise of better facilities. As participation by the universities was crucial to get the national authorities involved, the influence of FNT and SWB was weakened, but BioCity's role as a boundary object remained. MoE was enrolled, as BioCity was compatible with the policy of making biotechnology one of the national strengths. When accepting MoE's conditions for supporting the project, the universities had to give up some academic freedom and the idea of equal sharing of resources between departments. Instead, they had to learn to set priorities and to trust that better conditions for some units would profit the research community as a whole. Finally, the city of Turku was attracted to the BioCity project by the prospect of improved image and regional development.

The city's involvement in local biotechnology had started already with SWB, in which it was one of the co-financiers.[9] Later the city of Turku supported the birth of a broad research society in BioCity by giving the EUR 33 670 grant to FNT for planning BioCity. But it was MoE's views that forced and enabled a stronger commitment from the city's side. As MoE made it clear that there will be no BioCity without financial back-up from the city, the deputy mayor arranged a substantial sum of EUR 2.69 m for establishing a joint instrumentation centre in BioCity. This resource from the city was crucial both for keeping up the commitment of the national authorities as well as for bringing in the perspective of applied research. The city's interest was in supporting applied research and local businesses, so the city promoted the idea of an instrumentation centre that both the universities and the commercial enterprises at BioCity could use. The universities tended to think of the instrumentation centre in terms of basic research. Deputy mayor Määttä, however, pointed out that supporting basic research was the state's, not the city's, responsibility. The city of Turku also supported the construction of BioCity by buying congress centre facilities (600 m^2) in exchange for a port lot valued at approximately EUR 1.67 m. The purchase was in line with the city's ambitions of bringing visibility to the city as a centre of new technologies.

We argue that the relative lack of conflict around BioCity can be explained by the success of certain project builders to convince a heterogeneous set of actors that BioCity would be important for them and that they needed each other in order to realise it. In short, by promoting the idea of BioCity, they transformed the emerging biotechnology-centred interaction network into a network of mutual empowerment.

5.2. Losing the interest of the industry

The last BioCity committee, the one recommended by Jäppinen, soon announced that the universities would use 40% of the planned facilities. This was enough for the construction company to commit itself to the project. To avoid significant extra expenses

[9] The city of Turku supported the project with EUR 58 923.

that an upcoming new legislation would have incurred, construction was started already in September 1989, before any other tenancy agreements had been completed.

During the construction work, the BioCity process took a surprising turn. Until then, the plan had been that the supporting foundations of the universities would buy the universities' share of BioCity facilities and then rent them to the state, for the universities' use. MoE had prescribed the arrangement. In 1990, however, the Parliament of Finland approved a supplementary budget in which the Minister of Education, Taxell, introduced substantial funds for the purchase of research facilities for universities. BioCity in Turku gained the most (EUR 29.1 m). Other beneficiaries were Hermia in Tampere (EUR 11.4 m) and the Technical University of Lappeenranta (EUR 6.7 m). As a result, the state bought 10,600 m^2 in BioCity for the two universities and their joint Centre for Biotechnology. It is quite possible that this action of the state saved BioCity from atrophy in the grip of the impending deep depression of the Finnish economy. With the state firmly enrolled, BioCity appeared to be more or less irreversible, even in the face of significant failures, such as losing the commitment of many of the companies that originally intended to become tenants.

Although the key concept of "synergy" between academia and industry was played up in the rhetorics around BioCity, in practice the committees that planned BioCity neglected this dimension. It is true that people from several companies were members of FNT or the advisory group of SWB. Some of these "business people", such as the research directors of Wallac, Farmos and Leiras, were actively involved in the planning of BioCity. However, their drive and commitment did not necessarily reflect a commitment from their employers. In fact the interest of the companies turned out to be smaller than expected. From a strategic point of view, the strong emphasis on the university needs in the formal planning process left the lobbyists with little substance to offer to the companies. The various committees could not explain how the businesses actually would benefit from a presence in the building. Alko Corporation, for instance, wanted suggestions of "interesting, sound collaboration projects" already in 1988, when the planning of BioCity was in the very beginning, but none could be given at the time. In theoretical terms, even though the industry representatives participated in the interaction network, the network did not eventually form an empowerment network for the industry.

At first, the lack of visible synergies between academia and industry was not a problem for the project. FNT and the construction company YIT entered into negotiations with local pharmaceutical and food processing industry about the BioCity facilities. A group of companies had been involved in a VTT protein research project and were planning to continue this involvement within the framework of a VTT laboratory at BioCity. In the autumn of 1989, five companies and VTT had made written reservations of facilities. Negotiations were going on with seven other companies. At this stage, YIT had every reason to consider it a worthwhile risk to initiate the construction work without formal commitments from the companies. But gradually things started to change. VTT withdrew its reservation, followed by the food processing companies. Pharmaceutical companies like Leiras and Farmos restructured their activities, with delayed and reduced reservations as a result. It seems that the economic depression had forced at least some of the companies to re-consider the utility of their presence in a technology centre and to emphasise the need of situating their own research in close connection to production.

Uncertainties like these were, of course, a problem, but they never threatened the construction process. The state had already bought more than half of the facilities, and only one third of the building was reserved for companies. However, the loss of some of the industry commitment underlines the fact that the companies were not convinced of the empowering effect of BioCity. It seems that they considered their own location primarily in relation to their own activities and did not value participation in a network of other players in the field as much as the BioCity proponents had hoped for.

5.3. Stabilisation?

The BioCity building was finished in April 1992. By then, the sale of facilities had revived, approximately 70% had been sold. A few months later, there was already talk about a 90% occupancy. The Centre for Biotechnology, the university departments and research groups and companies like Valio and Raisio Yhtymä moved in. BioCity and its Centre for Biotechnology in particular had become the flagships of local biotechnology. However, this success soon turned out to be of a rather ambiguous nature. While BioCity brought attention to biotechnological research in Turku, it also created a misleading picture of the volume of that research. A substantial part of the local biotechnology research had *not* moved to BioCity. This was the case with most of the Department of Biochemistry and Food Chemistry, as well as the clinical research and the PET-centre of the Medical Faculty at the University of Turku. None of the medical departments moved to BioCity in their entirety. The MediCity floor at BioCity was primarily occupied by young researchers, while their professors remained in their old facilities. The unilateral focus on BioCity threatened to become a visibility problem for the biotechnology research that remained outside the building.

The unintended effects of BioCity became evident in the 1991 Ministry of Education mapping of Finnish biotechnology. The report contained positive evaluations of every biotechnology centre in the country, except for Turku (Ministry of Education, 1991). All it said about Turku was that BioCity was being built and that there would be a Centre for Biotechnology focusing on particular research fields. After complaints from Turku—as well as other universities, which also criticised the report—a new survey was done. To the representatives of Turku, the revised description of biotechnology in their city was more adequate but still confusing. The recently founded scientific advisory board of BioCity took upon itself to remedy the situation by organising the local biotechnological research within the framework of a new umbrella organisation, *BioCity Turku* (not to be mixed with BioCity, the building), which included all academic biotechnological research in Turku regardless of location. Thus, one of the first things the advisory board had to do was to displace the status that BioCity had gained: it had to demonstrate that BioCity and its Centre for Biotechnology were only parts of a larger framework of Turku biotechnology. Just like the BioCity project itself, the BioCity Turku organisation was, at least in the beginning, primarily a means of directing the flow of national funding to Turku. And again, the promoters of Turku were successful. In 1997, BioCity Turku was awarded the status of a national Centre of Excellence.[10]

The collaborative culture, which took shape in the process of planning and building the BioCity building, continued to grow in the wider context of BioCity Turku. One of the effects of this was that the instrumentation centre in the BioCity building was made available to the whole research community. The sharing of expensive instruments was praised by an international evaluation of Finnish biotechnology. The evaluation panel suggested that this particular model for collaboration should be spread to other cities and suggested that Tekes should start funding “robust facilities of this type, open to both academic and industrial use, in all significant biotechnology centres in Finland. This would be a major boost to the development of biotechnology” (Academy of Finland, 2002, p. 44).

6. Discussion

The commercial success of Turku’s bio-trajectory remains to be seen. It is possible that the bio-hype will crumble, that none of the companies will make a real commercial break-through and that the job generation remains more modest than estimated. But there is little doubt that the BioCity process laid the foundation for the regional biotechnology policy and, more importantly, regional co-operation thereafter. When the idea of BioCity was conceived, a heterogeneous set of interests backed up the plan and the regional emphasis was largely absent. The network around the technology centre became only gradually integrated with concerns about industrial and economic development in the region.

On a more general level, this study shows that our understanding of technology centres and science parks needs to be extended. The latter should not be considered merely in terms of technology transfer, as is common, but also in terms of social activity. Collaboration between actors is not just the result of technology centres and science parks; collaboration

[10] The Centre of Excellence Programme is a national science policy instrument. Centres of Excellence are high-quality research and researcher-training units that acquire guaranteed funding for a longer period than in conventional research funding.

can also give birth to them. In the Turku case, the negotiations leading to the construction of the BioCity building and the realisation of the BioCity idea resulted in a practice of collaboration and an accumulation of social capital that set the emerging cluster onto a very constructive trajectory of interaction.[11]

We believe that similar dynamics could be found in many other technology centres in Finland. A recent evaluation of the role of technology centres as sites for regional Centres of Expertise (CoE) in Finland also suggests this (Ministry of the Interior, 2003). The CoEs are a key tool in Finnish regional policy. Their objective is to help regions focus on the development of their core competencies in promising business areas. The evaluation notes that the technology centres functioned as co-ordination nodes within regional partnership-based networks, and goes on to state that "[t]he CoE organisations have brought together regional bodies implementing innovation policy in various advisory committees and management and expert groups and have created a framework for effective communication between the bodies" (Ministry of the Interior, 2003, p. 23). We have not studied the set-up phase of the other technology centres, but on the basis of the Turku case it can be hypothesised that the effectiveness of communication and co-operation around the technology centres springs from the processes of interaction preceding them—from the efforts to turn them into boundary objects acceptable for all parties.

The present study brings forth the significance of the informal but organised communication between key individuals from public and private organisations with the goal of defining and promoting strategies of future advancement of the technological field. This is not related to the short-term innovative activity, but is probably crucial for the long-term development of the milieu. In this, the bio-clustering in Turku follows a different—one could even say opposite—trajectory from the standard reference region in high technology and regional development, Silicon Valley.

Silicon Valley's development was originally driven by company formation, innovation and continuous re-configuration of the relationships between small companies. This changed somewhat in the 1990s, when the individualistic logic of the Valley was overcome by Joint Venture, a broad-based consortium of local businesses, governments and educational institutions addressing regional problems collectively (Saxenian, 2000/1996). There has thus been a shift of organisational experimentation and innovation from the level of the enterprise to the level of the region. In Turku, the development was collectively organised from the start, before most of the present-day biotechnology enterprises even existed. This probably is related to the nature of biotechnology, which requires rather massive laboratory infrastructures. In contrast to the ICT sector, new biotechnology firms simply cannot be started in garages. This is particularly true for the strictly regulated medical and nutritional fields that are strong in Turku. Here, a point that Stephen Cohen and Gary Fields (Cohen and Fields, 2000) forcefully put forward must be taken seriously, namely, that recent literature on regional development puts too much emphasis on social characteristics of the region and too little to the nature of the related industries and the technology that constitute their core. But the nature of biotechnology still seems to underline the social challenge involved: how to convince all relevant groups of the usefulness of investing in an infrastructure before there is any commercial activity in the field?

According to Etzkowitz, regions wanting to duplicate the success of Silicon Valley typically "build a science park, as a set of buildings, and ... expect the firms to magically appear, rather than to create an infrastructure for firm formation." He recommends as a more appropriate approach "to make an analysis of the strengths and gaps of the region and then design networks and organisations to bridge those gaps." (Etzkowitz, 2002b, p. 112). Even if the element of analysing regional needs was originally rather weak in Turku, the idea of technology centres was not just desperate optimism, but gained its strength from the brew of participants from different institutional backgrounds. Based on their analysis of the Cambridge area, Manuel Castells and Peter Hall (Castells and Hall, 2000/1994, p. 99) point to "the need to build up a network of individuals and institutions—a university, and in particular certain parts of it, a city council, a bank—that interact in certain positive ways. The

[11] The important role of the planning process is also recognised by Henry Etzkowitz, one of the creators of the Triple Helix theory, as he counts even the future projections as kind of technopoles: "in this format, the 'technopolis' initially provides a forum to bring local actors together to discuss initiatives" (Etzkowitz, 2002a).

recipe for that cannot simply be replicated from Cambridge or any other successful place; it has to be found, by a process that involves a great deal of serendipity, in each successive case."

What else can be said except that the actual historical configurations of these institutional structures are case specific? We propose that the Turku case helps us to re-consider the issue of trust and social capital in the context of high technology and regional development. The concept of trust has been shown to be essential for the functioning of industrial clusters. Stephen Cohen and Gary Fields (Cohen and Fields, 2000) argue that in Silicon Valley trust is not generated by civic engagement (Putnam, 1995), but by good company performance that creates trustworthy reputation and enables and strengthens the formation of innovation networks, which in turn strengthens the cluster-formation (see also Cooke and Morgan, 2000/1998). When explaining how this culture of trust and collaboration has been formed, they goes back to the individuals who established the first firms in the Silicon-Valley-to-be and the role of Stanford University in supporting these efforts. These firms were lucky to be formed at a time when the US government functioned as the lead-user of their products. A virtuous circle emerged with more firms and more innovation, accelerated by new venture capital and law firms that in addition to their services also served to connect the right people with the right firms. An appropriate infrastructure grew naturally around the initial community of firms.

But we claim that in the case of regional clusters the function of trust need not be restricted to commercial interactions nor be related to informal civic activities alone. Trust is also needed in defining win-win strategies that might lead to regional economic restructuring or infrastructure development. From the policy-maker's point of view it would be important to actively scan for and encourage self-organised activity and networking among the technological actors of the region. That the aspirations of existing networks include unwanted features from the policy-maker's point of view should not be a reason not to evaluate possibilities to participate in negotiations that may enable directing the process to a more desirable direction. The BioCity case presents several instances of productive collaboration despite the occurrence of initial suspicion; the strong involvement of a construction company was first considered suspicious by the city; the focus on industry needs was considered suspicious by the universities; and the emphasis on academia raised questions among some companies about the benefits of the technology centre.

The changing roles of university, industry and government have been discussed recently within the triple helix theory. Two interpretations have been presented (Etzkowitz, 2002c): either the triple helix participants "dance tango" together, having distinct roles but with linkages that enable them to move in tandem; or the participants are institutionally overlapping, each taking the role of the other and fulfilling multiple functions at the same time. Our interpretation of the Turku case falls into the first category. The interests of the actors and organisations were related to their institutional position in the traditional sense, even though these interests did not determine their actions, which were taken more or less "in tandem". Institutional overlap was after all rather modest: the universities were in the first place interested in securing resources for top-quality basic research; the industry was involved in university research and planning of research facilities as it seemed to offer potential access for interesting applications; the state and city governments acted as consensus-builders in order to encourage top-quality research and university-industry co-operation. But even in its modest form, the overlap was a new and sensitive issue that had to be tackled delicately. The participants gradually learned to trust each other enough to pull the project through: to show goodwill towards each other and commitment to mutually beneficial ends. The emergence of a suitable boundary object served as a tool in creating closer interaction between formerly separate actors. The BioCity process shows that self-organised networks may fruitfully—but not without risk—be harnessed to serve regional development.

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II

The fog of innovation: Innovativeness and deviance in developing new clinical testing equipment

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ABSTRACT

Even when innovators know they are working with a potential breakthrough innovation, they face formidable difficulties in assessing the exact ways it will be innovative as well as deviant in regard to extant systems, business and practices. This finding emerges from our case study that spans the 40-year history of an ongoing and by now potentially radical innovation in automated and miniaturized liquid processing. We analyze the changes in the system-to-be and its relationship to its future contexts throughout this period and show how the developers were able to reliably predict technical compatibility, the outcome, the interface points and effects towards the intended environment only some distance ahead. This 'fog of innovation' presents a management challenge not duly met by instruments available in innovation literature.

1. Introduction

The generally held image of innovation is that of a heroic quest for a breakthrough that can disrupt or create an industry and solve society-wide problems. The vast majority of technology projects, however, are incremental. It is towards these that the decades of accumulated managerial routine, instruments and scholarly thinking are geared. Even as there exists a considerable amount of literature on breakthrough projects, 'few empirical studies have identified the idiosyncrasies of the development process for radical and really new innovations and there is considerable anecdotal evidence that radical innovations require unique and sophisticated development strategies, but little empirical evidence to support these theories' (Garcia and Calantone, 2002). Further, most discontinuous innovation processes have been analyzed only when their outcomes and impacts have been readily identifiable. Indeed, the first thing people wish to know about potential innovation—laymen and investors alike—is 'what does it do, what impact will it have?' But what do we really know about how far inventors can specify such outcomes—the value, details and implications of the product—in an early *ongoing* innovation process? Some recent research has begun to recognize this uncertainty (e.g. Duret et al., 2000; O'Connor, 1998), and to underline the management challenge that lies in clarifying what kind of innovativeness—and, by the same token, deviance from extant solutions and markets—the innovation is likely to introduce, as decisions affecting innovativeness can have dramatic impact on the ability to advance the project. We seek to take such work further.

A key problem with the existing frameworks for analyzing ongoing (potentially) radical or discontinuous innovation processes is that they treat the very nature of the innovation-to-be as too evident and stable. For instance, innovation management literature regards the challenges relating to *innovativeness* as being mostly about the ways to frame the appropriate *business* case (Christensen and Raynor, 2003; Kim and Mauborgne, 2005). Most studies with management implications identify organizational structures and practices that would best meet the problems of idea-generation, uncertain markets, competency management in unfamiliar territories, and personality types suitable for advancing uncertain projects in potentially hostile or indifferent environments (Benner and Tushman, 2003; McDermott and O'Connor, 2002; Veryzer, 1998). The various sources of uncertainty and the methods of dealing with it have not been related to the inventions at the core of the project.

In a different line of research, approaches such as strategic niche management (Kemp et al., 1998) and transition management (Smith et al., 2005) stress accumulated capital, economies of scale in production, regulations, consumer habits and often decades of cumulative improvements and additions that allow the widespread extant technologies to 'entrench' against entrants. Targeting the innovation first to niches where selection pressure is less felt is said to allow potentially radical innovations to grow to a point where

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they can challenge the sociotechnical regime (Hoogma et al., 2002; Smith et al., 2005; Geels and Schot, 2007). In such studies relating to breakthrough innovations—be they electric cars (Hoogma et al., 2002) or new forms of water management (Hegger et al., 2007), for example—it has been considered evident that the innovation is discontinuous; the crucial task then becomes to learn *which* discontinuous framing might lead to success and how to pursue it.[1] Yet, we argue that in the early stages of *potentially* discontinuous projects it may not be evident whether—let alone which—discontinuous framing would be best suited. Some of the leading proponents of these approaches have started to give attention to the problems that the actors face. In the words of Geels (2004, p. 43): '. . .the multi-level perspective is a structuralist process approach, which provides an overall framework to analyze transitions. The approach needs to be complemented, however, with an actor-oriented approach working "from the inside out". Such an approach would look at how actors try to navigate transitions, how they develop visions and adapt them through searching and learning'.

An emphasis on social, cultural and regulatory (along with technical, organizational and business) embedment comes also from science and technology studies (e.g. Latour, 1996; Callon and Law, 1992; Jolivet et al., 2003) and other detailed case studies of innovation journeys (e.g. Van de Ven et al., 1999). These have given rise to approaches of periodic proactive evaluation for coaching (PROTEE, Duret et al., 2000; Hommels et al., 2007) for project managers (SOCROBUST, Laredo et al., 2002) and key stakeholders (ESTEEM, Jolivet et al., 2008). These approaches seek not only to identify the right people or determine the right framing, but to give tools for learning about the uncertainties in a project and the steps necessary to respond to these to make the project societally better accepted (Duret et al., 2000; Laredo et al., 2002; Jolivet et al., 2008). These tools include mapping the project history and its critical moments, the present techno-economic network (Callon, 1991), the de-facto scenarios of the future embedded in the project (Duret et al., 2000), and relating these to a future network and scenarios of the future working world. These lay the ground for contrasting the project's vision to external checks and clarifying the capacities for action the project has in affecting the concerns that have been identified (Laredo et al., 2002). While these analytics clarify the implications of the project well (Laredo et al., 2002, pp. 54–84; Jolivet et al., 2008, pp. 18–100), the means provided to de-script the future remain vague when it comes to the core of the project. In fact, only ESTEEM categorizes the novelty of each project and while it does this in six dimensions, the studies using the framework have resorted to doing so only once per project, neglecting possible later changes (Poti et al., 2006a,b).

All in all, we suspect that the existing research might have skipped too confidently over a set of thorny management issues about innovativeness and deviance. To investigate this empirically, we ask: *does innovativeness present a challenge for the management of ongoing, potentially discontinuous innovation projects*. With innovativeness we refer to those characteristics of the product that an actor perceives as having novelty-value (and with deviance to such novelty that an actor regards as providing negative value or just added burden). With management we refer to the de facto managing of an innovative project rather than to a specific managerial profession. With discontinuity we refer both to technology and market discontinuity.

We use a single case to make an exploratory study. To operationalize our concern, we ask how the innovativeness of the case project has changed during its development, and what have been the respective implications for the advancement of the project. The case at hand is a rare example of an ongoing project that *intends*, but has not yet succeeded in, launching an innovation that in its present form would be discontinuous both in the technological and market dimension of its respective industry (Garcia and Calantone, 2002). The innovation journey of this 'liquid microprocessor' (LMP) has continued from the 1960s to date with various ups and downs. While the ambition behind the journey—to automate chemical analyses—has prevailed, the focus of the innovation has shifted many times, producing several technical, social and business inventions and framings for the project.

To study the challenges that such shifting innovativeness poses, we deploy two complementary strategies. On the one hand, we provide a narrative from the perspective of the key actors about what they were doing and how they perceived the present and the future of their project. On the other hand, we adopt an analyst's point of view on the project and seek to more conceptually clarify the ways in which the project changed over the years.

The paper is structured as follows: we first clarify our analytic concepts, methods and data. We then proceed to the empirical case, which is divided into chronologically proceeding sections (Sections 3–5), each of which first presents a narrative of events and then an analytical description of the changes. This is followed by a discussion where we link the case analysis back to existing research outlined above.

2. Methods and data

We follow other qualitative studies in innovation in regarding the innovation as a 'journey' that is characterized by contingency but equally by accumulation of solutions and experience (Van de Ven et al., 1999; Pollock and Williams, 2008; Sorensen and Williams, 2002). We follow science and technology studies in discerning the gradually changing visions and re-evaluations, material realizations of R&D, organizational contexts and scenarios of the future (Hughes, 1988; Latour, 1987; Russell and Williams, 2002). We thus study whether and how innovativeness changed during the innovation process by focusing on the developers' changing articulations and understandings concerning the relation between emerging novelties and their implicated contexts. As we outlined in the introduction, there is presently no one analytic available that would characterize the changes in different aspects of the core of the project. At the same time the *findings* coming from innovation studies and science and technology studies indicate four complementary facets of innovation that at least need to be paid attention to[2]:

(1) The most rehearsed of these is the 'degree' of novelty. As is common in innovation taxonomies, we see it as ranging from business as usual to incremental to discontinuous (e.g. Tushman and Anderson, 1986; Benner and Tushman, 2003; Leifer et al., 2000).
(2) The degree of novelty appears different depending on the perspective (Afuaf and Bahram, 1995; Garcia and Calantone, 2002): to whom and in what respect is an innovation novel? For example, a technically incremental application can become

[1] We are grateful to one of our reviewers for clarifying this distinction.

[2] We hence stress that the aspects outlined below are not an eclectic mix from different theoretical positions, but reflect relatively well established findings about different facets of innovativeness. In discussing the 'dimensions' we chose to leave visible some of the alternative ways this aspect has been addressed, but in discussing the other three aspects we identify only the main sources due to limits of space. The sprawl of concepts describing closely similar empirical phenomena used in innovation and technology studies is well documented (for one of the best comparisons see Russell and Williams, 2002) and in the space of this article there is no possibility to properly compare the range of terms by which these aspects have been dealt with in different studies.

a major novelty for a new group of users, or a technologically radical novelty may revolutionize the sub-contracting network but be invisible for the end-user. Techno-economic networks (Callon, 1991) address this issue by differentiating between four poles: technological/industry, science, regulation, and market/users. The CreateAcceptance project expands this to seven dimensions: law and regulation, social, cultural, economic/market, institutional, infrastructural, and technological (Poti et al., 2006a,b; Jolivet et al., 2008; close affinity Hoogma et al., 2002, pp. 28–29). In our appraisal, Lettl et al. (2006) address the issue more clearly with four dimensions that include the 'technological' and 'market' dimensions, the novelty for the organization developing the innovation as the 'organizational' dimension, and the rest of the above listed within the 'environmental and institutional' dimension. This is the terminology we follow below.

(3) Innovativeness may reside in more than one place or 'locus' within and around the product. Changes can occur or be implied in the underlying technological, scientific or organizing principles, components, in the product architecture, in user practices or even in the existing regime. Indeed, structural features have been shown to bear upon the relative ease or difficulty of introducing an innovation (Henderson and Clark, 1990; Gatignon et al., 2002). By dividing the product concept into these loci we can pinpoint where the project's innovative activity—problem-recognition, envisioning, inventing and development work—was focused, and where no innovative activity took place.

(4) Finally, not all techno-economic networks and all their loci are even or alike. 'The seamless web' (Hughes, 1988) is not fully seamless at all times and places, and we found it necessary to distinguish (a) how seamlessly related the dimensions of innovation appear for the developers—for instance how strongly changes in technological details demand changes in the organization of user practices or in the relevant regulatory measures, and (b) how tightly or loosely coupled a system (or configuration) the invention's locus of application appears to be, that is, how seamlessly the product has to fit in with extant instruments and procedures (Fleck, 1993; Russell and Williams, 2002).

The case history is divided into three periods, and following the description of each period we assume an analysts perspective to the developers' understanding of the innovation-to-be, trying to keep *simultaneously in sight* the above four facets of innovation, illustrating the changing loci of innovative activity further in Tables 1–3.

In terms of data we have had access to extensive archival material. There are over a hundred full folders of paper remaining of the project from the period between 1960 and 2008 (if stacked this makes over a 10-m pile!) and in addition over 4000 electric entries on hard drives from the years 1994 to 2008. Typical items are patents, contracts, reports, inquiries, technical reports, correspondence and newspaper clippings. We chose to intertwine the document analysis with a total of eighteen semi-structured interviews of 1–3 h in length, dozens of email exchanges, as well as informal chats and short conversations over the phone and face-to-face. The main innovator was formally interviewed eight times, while other stakeholders formally once or twice. From 2005 on we also have notes from the direct observations of meetings, funding negotiations, technical work, et cetera, as the first author has been an observing and commenting participant in the process.

In the document analysis we followed the principles of historiographic source criticism (e.g. Tosh, 1991) in which we have formal training as both authors have an MA in history. Interviews were analyzed by content, and the views of different actors were systematically compared (Silverman, 1993; Kvale, 1996). Further data and method triangulation was used in comparing the interviews and documents (Denzin, 1989). The analysis proceeded as follows: we first sketched the rough outline of the process with multiple interviews with the key inventor and then searched documents related to the key events and interpretations. The next step was to conduct a round of interviews with eight stakeholders and intertwine these with further document analysis. The preliminary outcomes were several chronologies and narratives of the process, which we gave to our informants for comments, including the draft version of the present paper. A further round of interviews and document analysis ensued in response to reviewer comments—while most of this merely confirmed previous analysis, it did provide a somewhat better position to clarify the early visions of the LMP in the 1970s and 1980s.

3. From a technically discontinuous small-market innovation to a potential breakthrough

In this first empirical section we describe the origins of the technological discontinuity. In the end of the section, we analyze how the locus of the innovative activity moved from one application to another, and diagnose the developers' perception of the meaning of the shift.

The line of inventions began with frustration with human errors. The inventor, while doing laboratory rat tests in 1966 at the University of Turku, Finland, discovered that the method of manual sample preparation severely compromised the accuracy of measurements. He invented a metallic microstructure that enabled a hundredfold improvement in accuracy as well as the automation of sample handling. A representative of U.S.-based SCINS [Scientific Instruments] visited the lab, and, on understanding the situation, provided a grant to build a decent prototype. This eventually led to three generations of 'Sample Oxidizers', which formed a technically discontinuous but market-wise continuous innovation for SCINS and came to dominate the market in sample preparation soon after the introduction of the first generation in 1969. As the development was done abroad, SCINS never integrated the project into its internal R&D department, but funded a small Advanced Instruments Research Group (AIRG) in Finland wherein know-how of the new technology remained.

The group dreamed of a further all-purpose automated method that could provide unforeseen accuracy in chemical analyzes. The solution was to be a miniaturized closed system akin to the Oxidizers. The problem was to find a suitable valve for controlling the liquids on a micro scale after all the mechanical ports, tested in the Oxidizers, turned out to leak or retain dead volumes of liquid. Then chance favored a prepared mind: an Oxidizer blew up an entire laboratory in the US in 1972. Trouble-shooting revealed that users' alterations had caused one of the tiny tubes (1 mm in diameter) to freeze. Melting such a clog required 2000 bars pressure in its $-20\,^{\circ}\mathrm{C}$ state, or great amounts of energy and time if done by heating the whole system. The damned clog was an incredible plug! Yet it was evident that very little energy would be needed if there was a way of applying heat directly to the clog. The idea of an ice-valve dawned: whereas existing technology used gravity to keep liquids in open vessels during analytical steps, liquids could be controlled by freezing and thawing ice plugs in the closed microfluidic environment. With this radical invention the group's dead-end was conceptually solved in 1973, and by 1977 the group had concluded that it would be possible to build a generic 'liquid microprocessor' (LMP) for the automatic processing of extremely small liquid volumes.

Enthusiasm was high. The LMP seemed to offer significant advantages by removing manual errors from analytical steps '[i]n clinical chemistry laboratory [due to]:

Table 1
A shift in innovative activity from Oxidizers to the LMP project. The locus where the original problem was perceived to be is marked by *. The locus of the envisioned product is marked by ¤. The main loci of development work are marked by #. *Italics* mark envisioned but not completed work; brackets () mark loci that were assumed not to require innovative work.

Locus	Oxidizer in 1970	LMP by 1977	For comparison: respective elements in conventional clinical testing
Regime/sector	(Biochemical scientific research)	(Health care, water management)	Health care/Clinical diagnostic process
User practice	*(Measurement of radioactive markers in research laboratories)	*(Any practice utilizing chemical analyses, esp. clinical laboratories)	Clinical laboratory
Artefact	¤(Sample Oxidizer)	¤(*Analyzer*)	Laboratory analyzer
Artefact subsystems	Electroformed channels for processing liquids and gas	¤*Liquid microprocessor*	Various mechanical subsystems for performing the analyzer functions
Components	#Commercially available, unsatisfactory valves	#*Electroformed channels for ice valves*	Test tubes & cuvettes (for containing and moving liquids)
Principles	Automation #Mechanical valves Closed system for liquid–gas processing	*Automation* #Phase-change valves *Closed hermetic system for liquid processing*	Mechanization Liquids kept in test tubes by gravity Non-hermetic system for liquid processing

1. Greatly reduced costs/test, because microvolumes of the present reagents used. A huge gain in cost/speed. Ten times the speed of any present autoanalyzer.
2. Reduced general costs, because of less negative tests.
3. Better quality control, reliability.
4. Less laboratory manpower.'[3]

Indeed, the LMP appeared to represent a leap in long-standing attempts at reconciling 'the two fundamental and inherent contradictions [of clinical chemistry]: (1) to use as small a sample as possible or available, without exceeding the limit of detection; and (2) to achieve speed without sacrificing precision of analysis' (Rosenfeld, 1999).

These visions were closely bound to the dawning capabilities of the system—they were no fantastic leaps in this regard. 'Every single important aspect of this functional system based on SVV [LMP] has been shown or tested in bits and pieces in AIRG laboratories since 2nd September 1972.'[4] However, the vision's relation to the constraints and requirements of the application domains remained unspecified. An enormous business opportunity was expected from a bundle of generic improvements: '[t]he number of hospital days per patient can be reduced... in emergencies very fast [diagnostic] action can be accomplished'.[5] As recognized by the key innovator himself: 'This list [of potential applications] is endless but I have not put too much time in systematically studying it.'[6]

At this stage, we wish to take an analytic look at the innovativeness of the project.

The developers had first-hand experience of the research laboratory, which formed the locus of user practice (see Table 1) where cumbersome manual sample preparation had emerged as the problem driving the Oxidizer development. In the LMP project, the relevant industrial field changed from scientific instruments to clinical diagnostic equipment. The motivation was to eliminate the sources of inaccuracy introduced by manual user practice in all (bio)chemical testing, but the locus of the respective product was unclear: it was first without elaboration, then conceived of as an artefact subsystem ('LMP system'), and later an artefact ('LMP analyzer'). Table 1 presents the shift of innovative activity from the principles, components and subsystems of Oxidizers to those of the LMP.

[3] Document "Revolution in health care by SVV [LMP] systems', dated 5.6.1977 (beginning) and 14.7.1977 (end), written by the main inventor to convince SCINS to fund more R&D.
[4] Ibid.
[5] Ibid.
[6] Ibid.

The nature of innovativeness the LMP product would introduce remained loosely articulated. This was partly because the developers were not aware of the differences between scientific and clinical laboratories—neither had they developed instruments for clinical use. Regardless—or perhaps because of this—the LMP was assumed to turn into a generative innovation that would transform a much broader and more complex locus than the Oxidizers had done.

The type of envisioning done in the LMP project has been found typical of early stages of 'promising technology' (e.g. Lente and Rip, 1998; Russell, 2006). A strong, even hyperbolic trust in the capabilities of the promised technology and capabilities to produce it are conveyed to enroll supporting actors. The envisioning of applications is without much precision or certainty and builds on advances in other fields as well as yet-to-be-articulated requirements and constraints of particular business applications. Indeed, the *degree of novelty* of the LMP technology became articulated only in the *technical dimension*, where its discontinuity was evident. The visions entailed innovativeness in other dimensions as well, but there was little consideration of the exact implications. Similarly, the choice of clinical chemistry as the primary application area—as opposed to water management, which was also considered—was partly due to the developers' view that an advance in clinical instrumentation could have far-reaching effects (in our analytical terms the field was regarded relatively *seamless*), but the exact manner of how the LMP was to fit in was shrouded in the mist. In fact, the next phase in the development work reveals that not even the tightness of couplings between the components *internal* to the LMP could be anticipated before they could eventually be tested.

4. Dawning of business, science, manufacturing and usage discontinuities

In this second part of our case analysis, we show how the downside of the technological discontinuity gradually became evident for the developers as they learned that the innovativeness of the LMP was regarded as a valueless deviance in the wrong direction.

SCINS' competition in sample preparation equipment, chemistry and supplies evaporated during the 1970s. The firm had little interest in funding an uncertain, long-term innovation project for clinical use. The inventor left SCINS, recovered his ice-valve patents and started his own company in Finland in 1977. After a successful line of innovation, there was a strong sense that it would only be to SCINS' loss not to jump on the emerging bandwagon. Negotiations with several companies progressed frustratingly slowly until the marketing department of a U.S.-based computer company with an interest in the diagnostic industry made an offer of $5.5M. The intention was to design '*a blood chemistry analyzer*'.[7]

Instead, however, the inventor accepted a competing offer from Finnish TEL [Telecommunications and Electronics] and MUF [Multi-Field]. They had been following the inventor's negotiations with the large U.S. company and, at the time, had stakes in diagnostic equipment. The joint venture was '*to develop micro-electro-thermo-fluidic equipment products and sell sub-licenses*'.[8] The financiers' explicit agenda was cost savings, '*The removing of mechanical parts was the advantage; [an analyzer] is cheaper to produce when there are no moving parts*... *We did not see that it would differ from existing analyzers in other respects*' (Interview with the main inventor 5.4.2008). Nevertheless, the inventor's 'hidden agenda' was to improve the accuracy of chemical analysis by automation, as he had done in sample preparation already.

The development progressed through new problems and inventions. A novel reagent package was patented (filed in 1985) and a centrifuge was integrated to the apparatus in 1986. Then ice valves needed improvement. TEL had insisted on using its existing construction technology and materials, and MUF its own production methods. Only after TEL withdrew from the venture in 1985 was it possible to return to developing the original Oxidizer-type materials and create operable channels by 1990. More precision was now needed in liquid dispensing, and it was gained by 1996; and, once the opening of ice valves was reconfigured by 1999 through the use of by then commercially available cheap lasers, the inefficiency of the heating was solved too, clearing one of the final major technical issues.

All in all, it was gradually realized that in order to benefit from the increased accuracy, an increasing number of the analyzer functions (such as dispensing, mixing, incubation, measurement and washing) needed to be built anew just for the LMP. Towards the turn of the millennium it became evident that the performance of the LMP was useless if samples and reagents came, *at any point* in the analysis, into contact with air. The gradual creation of an alternative, fully hermetically sealed system was slow, as all components related to liquid handling had to be developed in-house.[9]

However, difficulties in the business, organizational and environmental dimensions of the innovation overshadowed technical advances. These began with the incumbent patron company MUF already during the 1980s. The diminished use of reagents became an issue for the parent company, as reagents were its main income. Later, it dawned that the hermetic, closed nature of the system made the role of the laboratory, the customer, somewhat questionable, as the LMP in effect attempted to black-box the work done in the laboratory. Besides, the LMP was incompatible with central laboratories, which used parallel processing of samples whereas the LMP could analyze just one sample at a time. MUF insisted in its monthly reviews that the LMP must be used to improve conventional technology, but no such initiative paid off. The performance of the technology was considered too good and the investments already made too significant to discard lightly, however.

Continuation became possible as the development of the LMP was, for a time, paid for by other firms that hoped to use the LMP in their analyzers. But, eventually, there emerged a sense that integrating the LMP to the existing systems of the clinical laboratory would produce endless technical solutions without a marketable application. Eventually the company got a new majority owner, the LMP was shelved and work focused instead on an add-on innovation to the LMP, the 'bellows dispenser', which had resulted from the efforts at hydraulic dispensing.[10]

Another disappointment came from scientific audiences. The technological commitments defined the range of questions that were scientifically or otherwise interesting for conference audiences: scientists in microfluidics dismissed the LMP for not being based on silicon (the evolution of this line of microfluidics is described in Robinson and Propp, 2008), while experts in laboratory automation considered the LMP a hoax. The claim of negligible 0.001% carry-over (from one liquid batch to another) was deemed outrageous, since the laboratory experts knew that (all other) microfluidic structures were flat (rather than round), and absolutely not cleanable. The inventor failed to communicate that cleaning became possible through the hydraulic principle, the zero dead volume, etc. '*The problem was that there had emerged phenomena for which there were no words, no concepts. When explained with old concepts those phenomena appeared as lies, they didn't fit, they were impossible. There was a whole chain of phenomena and operations that one should have been able to communicate, but at the time we hadn't yet formed those concepts, so everyone thought that we must be cheating*' (Inventor's telephone comment on the article manuscript 23.1.2009).

The full scope of the disjunctive features of the LMP began to dawn when the owners wanted to sell the LMP patents in 2000, and failed miserably. The inventor, together with an outside consultant, met representatives from various diagnostic companies. They were often initially interested, but invariably changed their opinion, some explicitly claiming that the invention would destroy their business.

Let us again assume an analyst position to clarify the changes in the innovativeness and deviance the project was perceived to introduce. Throughout the 1980s and 1990s technical incompatibility caused more and more of the analyzer functions to be incorporated into the LMP (see Table 2). This, in turn, revealed that the LMP might turn out to be business-destroying in the *market dimension* for the patron company by undermining its sales of reagents and other equipment. Further, the LMP's serial rather than parallel drive was incompatible with how the clientele (clinical laboratories) organized their practices, which might, in turn, demand seeking new clients. The LMP also threatened to become competence-destroying in the *organizational dimension* by making obsolete the competencies of MUF in other clinical products such as reagents and disposables. In the *environmental dimension*, other incumbents and potential patrons as well as scientific communities connected with clinical chemistry remained doubtful of the innovation.

Table 2 illustrates how the technical novelties accumulated while the product concept came to a dead-end. The gradual work with developing artefact subsystems and components for 'airless' analyzer functions was only enabled by the innovative broadening of the principles on which the system was based. The net result was that the hermetic solutions began to form their own development pathway increasingly separated from conventional clinical chemistry equipment. Meanwhile, despite accumulating inventions, the LMP project partners lost consensus about what problem the LMP

[7] According to an agreement proposed by the computer company on 1.3.1979.

[8] Agreement between TEL, MUF and the inventor's company. 4.4.1979.

[9] For example, in the conventional dispensing method (syringe + flexible tube + probe) sample and reagent are separated by an air meniscus in the tube. But air compresses by six orders of magnitude more than liquid. The functionality of the LMP required the removal of air, because the volume of liquid that enters the system had to be measured with much more precision. In theory, six more digits were possible in a hermetically sealed environment. But there was an even more fundamental reason: any presence of air in LMP channels whose diameter is measured in fractions of a millimeter introduces powerful surface tension and capillary forces—as a consequence liquids move erratically. A hydraulic, airless, dispensing method had to be invented.

[10] The dispenser could also be used independently for accurate dosing of small amounts of liquids. The dispenser was highly durable, which meant that it would have cut MUF's after-sales of disposable syringes and was only commercialized under the next majority owner—in close affinity to the fate of some other LMP parts.

Table 2
The rise of a 'hermetic pathway'—the fall of a product concept. The locus where the original problem was perceived to be is marked by *. The locus of the envisioned product is marked by ¤. The main loci of work are marked by #. *Italics* mark envisioned but not completed work; brackets () mark loci that were assumed not to require innovative work.

Locus	LMP by 1980	LMP by 1990	LMP by 2000	For comparison: conventional clinical testing
Regime/sector	(Health care)	(Health care)	?	Health care
User practice	*(Clinical laboratory)	*(Clinical laboratory)	?	Clinical laboratory
Artefact	¤*(Analyzer)*	¤*(Analyzer)*	*Integrated analyzer* → ¤bellows dispenser	Analyzer
Artefact subsystems	*Liquid microprocessor* with extant analyzer functions	#¤*Liquid microprocessor* with some novel and some extant analyzer functions	*Liquid microprocessor* with all novel analyzer functions but reaction measurement	Various mechanical subsystems for performing the analyzer functions
Components	#Electroformed channels for ice valves	#As before + other capillary channels, reagent bags, syringe-dispenser, *better heating method*, *bellows dispenser*	As before + laser heating, integrated mixer-incubator, digital bellows dispenser	Syringe dispenser, test tube, rotating plates, plastic cuvettes, etc.
Principles	*Automatic, hermetic system* for liquid processing, based on phase changes	# *Automatic*, hermetic *and hydraulic system* for liquid processing, based on phase changes *and pressure changes*	As before + based on phase changes and digitally controlled pressure changes	Liquids kept in test tubes by gravity; moved between vessels mechanically. Non-hermetic system for liquid processing

was out to solve, the contexts it implicated in user practices, as well as expectations regarding the product.

Finally, these dimensions of innovation (and the stakeholders involved) at the targeted locus of application, the clinical laboratory, turned out to be more *tightly related* in regards to entrants like the LMP than was expected: the market and distribution of analyzers and supplements was divided among few large incumbents, and the scientific knowledge in producing and using the equipment had changed along an incremental path for a long time (Rosenfeld, 1999). Even when a whole bundle of additional inventions was in place, the LMP's promises lost their potency when it became evident that it would have to challenge the well-serving arrangements in existing instrumentation and business. The potentially increased innovativeness hence turned into mere increased deviance for all the expected audiences.

5. Disruptive framings of innovation

In this final section of case analysis, we focus on how the previous experience enabled the developers to conceive the innovation-to-be from a perspective that expanded its value-enhancing innovativeness, and how to better handle the deviance that needed to be introduced.

As the patent rights were commercially useless, the inventor was allowed to buy them back. But... to what purpose? He decided to focus on all of the technology's strengths: what customer-related issues *could* it solve?

The one taken-for-granted assumption covering the entire clinical diagnostics was that the *laboratory* was *the* place for extracting information from patient samples. Even the existing point-of-care (POC) applications were only *add-ons* to the laboratory, never replacements. But the LMP as a near-patient system might go further. Technically, real-time analyses for one patient at a time at the health care site would not require the parallel drive that the LMP lacked. The LMP system could generate MUF's results for routine tests in just few minutes and with greater, not lesser accuracy than the laboratory. As consumption was extremely low, enough reagents for 6-month use could be stored hermetically within the PC-sized device. The digital pressure and temperature signals of the analyzer would make remote monitoring of service-needs and quality control possible via the Internet. The end-customer benefits would include the possibility of using the same blood sample in follow-up tests, which would, in turn, cut the need for patients to return for new sampling. And neither would samples need to be transported possibly dozens of kilometres to a central laboratory. These benefits were significant to the entire health care system.[11] The real revelation was, however, the business idea: the apparently impenetrable value network of incumbents could be bypassed if the use of the technology was offered as a *service*. The customer would only pay for the tests, not for the device. No laboratory, no incumbent business, no entrenched science or technology would be needed![12]

The inventor decided to form a company, DITS [Distributed Testing Service], for commercializing the concept, applied for a patent for the respective—potentially disruptive—system invention, and convinced two of his brothers to join in to purchase the LMP patent rights and production technology.

But from these assets it was a long way to a functioning diagnostic system with working and appropriate testing servers, ICT-interfaces, and the functions of a central operator, service provider, and so on. A few million euros were needed for prototype-development, as one needed to set up and optimize the serial production method for high quality core LMP components that would function seamlessly together.

In 2000, the inventor approached the telemedicine department of a Finnish teleoperator. There was enthusiasm, but there were also delays and eventually no deal because the operator dismantled its telemedicine department in a merger in 2004. There were numerous other partnering efforts; for instance, a German reagent company, a U.S. based information technology company, two Nordic telecommunications companies, a representative of clinical research organizations, and an Indian company were approached, along with Finnish and EU funding bodies, programs and research institutes.

Different ways to frame innovativeness were tailored according to the needs and resources of the partner-candidates. The selection of these contacts was mostly done on the basis that their interests would deviate from the conventional diagnostic business model but not from those of DITS. For example, the teleservice of DITS was presented as an extension of the teleoperator's existing business, while it remained unclear whether the service model actually required innovative input from the operator in business or in IT. For clinical research organizations the innovativeness of DITS

[11] Many of these ideas were envisioned informally already in a draft of the inventor's unpursued research plan, University of Turku, dated 25.4.1994, but rejected in the LMP company context leaving little point in pursuing them further at the time.

[12] The service-concept was in fact a necessity since the analyzers would need a professional re-fill of hermetically packaged reagents every 6–24 months.

was presented as being in the ability to achieve high-quality testing location-independently, and for a reagent manufacturer it was framed as a possibility for having a new role as a service-providing partner rather than a vendor of bulk products. Conveying such a semi-flexible business plan proved tricky and there were also limits to the finetuning involved: public funding programs often turned out to be targeted towards generally recognized industrial structures and problems and deviation from such aims could not be masked.

The situation was complicated by issues of control. Most partner and investor candidates wished for more evidence from the DITS concept or wanted full control over it, only to be turned down—the developers perceived them lacking the hard-won lessons of the 1980s and 1990s. The partner candidates outside clinical chemistry regarded the terms as too poor or the concept as too alien to justify entering into a new business. No longer surprisingly, the incumbents were not keen to disrupt their own field. At best, a large diagnostic company considered using LMP technology to calibrate its lab-on-a-chip products, but did not want other applications. By 2007, only EU's EUREKA, The Finnish Funding Agency for Technology and Innovation and one reagent manufacturer remained as prospects that regarded the innovation as potentially valuable with respect to their goals *and* would not hinder the management of one or another dimension of innovation. To its good fortune the project received EUREKA funding in July 2008, covering the design and building of prototypes and the initial validation of the system (in total, 50 person-years) crucial for gaining further rounds of investments.

While large-scale funding was being sought, the project survived for 8 years with modest resources, mostly mobilized from the regional innovation environment. In 2005, facilities were found within the bio-incubator of the Turku Science Park, also enabling collaboration with a local polytechnic through student theses, and providing consultants to aid with, for instance, the creation of business plans. A manufacturing company allowed the developers to use its know-how and facilities in the hopes of later producing DITS servers and components. A professional CEO, a project leader, a laboratory leader, and an expert in clinical and laboratory work, who became the next CEO, joined in due to being familiar with either the LMP project or Oxidizers. The users' motivation was to '*advance one's own field*', as one of them put it, being deeply discomforted about the host of logistic and reliability problems—for example, '*tired of the stupid guarding to ensure that lab assistants don't leave the reagent packages too close to the back-end of the refrigerator for the night*' (Interview with the laboratory leader 8.3.2006). These kinds of local resources allowed the innovation project to inch closer to the building of a prototype and clarifying the business-case and customer-value of the concept.

An important aspect of this work was the emergence of technical, conceptual and business 'add-on' inventions that, again, altered the possible ways of framing the concept. To give a better idea of the contingencies involved, let us examine a development path that opened up a new possibility for framing the innovation as a quality control system. This began as a realization that the service concept might not work: while there were reagents that remained stable for months, human control serum did not. Re-filling servers every few weeks at user-sites would have been unfeasible. It was known that the hermetic ice valve would retain the serum 'virtually unopened', extending its life. And, it dawned that the serum did not even need to stay perfectly stable as long as one would know precisely how it changed. Such subtle changes could not have been measured by other means, but the LMP excelled at that. One problem remained, however: where to find an independent point of comparison? To date, quality control had been laboratory-specific. The same sample, tested in two laboratories with identical methods, was not likely to produce precisely identical results. There was only the indirect, labor-intensive standard method for ensuring that control test results were close to reality. However, in the distributed DITS system several servers could be loaded with small amounts of control serum taken from the same lot, hence jointly revealing any dissenting daily control test value before it grew biologically significant. No-one had conceived of the idea of grid-type networking and the use of an identical control serum before, as it was not practically realizable.[13]

The innovation network was increasingly confident and optimistic. This was supported by a prominent diagnostic market research report predicting that the future of in vitro diagnostic industry depends on the emergence of point-of-care testing with performance matching that of a central laboratory test results. The report judged that present technology is too 'stagnant' to power this next industry life cycle.[14]

One issue needed to be solved, though: how to turn quality control into a tangible asset? Guidelines and standards presented themselves as the prime place to turn. The inventor was an observing member in an international working group for guidelines on future quality assurance. While there were wishes that manufacturers take responsibility for risk reduction, the work was actually focused on increasing the number of procedures of the laboratory staff.[15] The ambition of DITS to black-box and automate the procedures performed by people was, in theory, compatible with the aims of the standards, but the means obviously deviated from those required. Very robust demonstrations would be needed to counter the likely incredulity and resistance to such a solution. Thus, once again, the potential way forward was shrouded—this time by the proven techniques and the vested interests of the industrial and scientific experts that informed the regulators.

Let us again clarify the changes in the innovativeness with the help of more analytic terminology. The disruptive framing resulted from accumulated experience from the domains the LMP/DTS concept was to face. When compared with the vision of the 1970s, the new vision articulated far more precisely the innovation's immediate contexts and interface points. In Table 3, the actors' realization that quality control is a critical issue for DITS is analytically recognized as the added 'System/ensemble' locus, situated between the artefacts and users that control the artefacts. The table shows how, while there was only incremental improvement in the underlying LMP technology, its discontinuity with laboratory testing was solved by *expanding the loci of the envisioned product* from artefact to service in the user practice locus, while it started to become evident that innovative activities might have to be expanded even further to prepare the ground for such a product. The laboratory in its present form would be re-aligned with location-independent networked testing, an unforeseen remote quality control method, and a new business logic—thoughts turned towards the diagnostic process at large.

The new inventions involved a relatively high *degree of novelty* along at least some of their *dimensions*: remote quality control was discontinuous standards-wise and organizationally; the service business was discontinuous business-wise (yet location-independent testing was meant to be continuous, even incremental, from the point of view of the doctor who orders tests—the results would be similar but faster).

[13] The International Searching Authority of the Patent Cooperation Treaty found nothing to compromise the novelty of the quality-control patent in its response as of December 12, 2006—meaning that no one had filed comparable claims before.

[14] *Point of care diagnostic testing world markets. Trends, industry participants, product overviews and market drivers*. TriMark Publications. April 2007. Volume TMRPOC07-0416, p. 187.

[15] Clinical and Laboratory Standards Institute (2005), *Proceedings from the* QC for the Future *Workshop; A Report.* CLSI document X6-R. Clinical and Laboratory Standards Institute, Pennsylvania USA.

Table 3
The characteristics and development of the distributed testing service (DITS) system compared with the characteristics of a conventional clinical testing system. The locus where the original problem was perceived to be is marked by *. The locus of the envisioned product is marked by ¤. The main locus of work is marked by #. *Italics* mark envisioned but not completed work; brackets () mark issues that were assumed not to require innovative work.

Locus	DITS in 2000	DITS in 2008	For comparison: conventional clinical testing
Regime/sector	*(Health care: faster clinical diagnostic process)*	*Health care: faster clinical diagnostic process*	Health care: clinical diagnostic process
User practice	*,¤,# *Location-independent testing-service*	*,¤,# *Location-independent testing-service*	Clinical testing: centralized laboratories + point-of-care tests
System/ensemble	*(Automatic quality control)*	# *Quality control by on-line pooling and automatic performing and analysis of quality control test results*	Quality control by laboratory staff
Artefact	*Networked analyzers*	# *Networked analyzers*	Laboratory analyzers
Artefact subsystems	*Integrated liquid microprocessor*	# *Integrated* liquid microprocessor	Various mechanical subsystems for performing the analyzer functions
Components	Electroformed capillary channels where liquids move and ice valves function, laser heating, reagent bags, digital bellows dispenser, integrated mixer-incubator	# As before + prototypes for *the serial production of core components,* refrigerator, insulated cover, *operation control software, nexus to local health information systems*	Syringe dispenser, test tubes, rotating plates, plastic cuvettes, etc.
Principles	*Automatic,* digitally controlled, hermetic, hydraulic and *networked system* for liquid processing, based on phase changes and pressure changes	# As before + *based also on remote quality control*	Liquids kept in test tubes by gravity, moved between vessels mechanically. Open system for liquid processing. Local quality control

The changes in the degree of novelty in different dimensions also changed the expected relation between the actors in the field: this way of organizing routine testing would be free of pressures to centralize it, the customer could be either a laboratory or a health care facility directly—or a licensed DITS service-provider, a role possible both for existing and emerging diagnostic companies.

These recent add-on inventions underscore the problems that result from expanding the innovative concept in the wake of making it disruptive. The business credibility of DITS depends significantly on the new quality control method; advancing it requires demonstrating the technology in practice; to find funding and partners to demonstrate the technology is, in turn, difficult as long as the regulatory and business ambiguity remains; the ways in which the faster testing would affect appointments in future user sites can be anticipated only to a limited extent before field trials. Indeed, when the dimensions of innovativeness turn out to be nearly seamlessly related in all available framings of the innovation, the number of interrelated issues grows, the targets become more and more ambitious and the amount of work still needed grows rather than diminishes, even when the scope and appeal of the overall innovation may be enhanced. There is hence an obvious downside to framing the potential breakthrough innovation so that its locus would expand: it removes some uncertainties but introduces a host of others. Anticipating and clarifying the likely changes in innovativeness and deviance in different configurations and framings of the project hence seems to present an unavoidable and continuous management concern for an ongoing discontinuous innovation project at least throughout its gestation and early development phases.

6. Discussion

Empirical studies of ongoing discontinuous innovation processes, particularly their early phases, are rare. The timeframes of their completion tend to exceed those of typical research projects and all the while it remains uncertain whether the quest will eventually amount to anything at all. Attempts at reconstructing projects before their clear success (or failure) hold, however, potential advantages, since the innovators tend to rationalize their accounts and smooth over the contingencies, idiosyncrasies and retrospectively false turns in typical post-factual accounts (Bijker, 1995). With this in mind, the study of the ongoing and by now potentially radical LMP presents a window onto the emergence and perception of novelty during such a process, allowing us to deepen the understanding of the management challenges involved.

The case analysis revealed that innovativeness posed a management challenge for the potentially discontinuous innovation process in at least two ways, one related to the project's internal dynamics (understanding innovativeness), the other to its perception by outsiders (presenting innovativeness). The project gradually moved into an alternative technological pathway: from mechanization to automation, from an open to a closed system, from gravity-based to temperature-based liquid control, from analogical to digital pressure control, from local to networked solutions. All the while the developers were able to reliably predict technical compatibility, the outcome, the interface points and effects towards the intended environment *only some distance ahead*. This situation was further obscured by what could be called conceptual discontinuity—the lack of accurate terms, concepts, and traditions to elaborate and contextualize the work, the components, and especially the underlying principles. Taken together, these issues formed a long learning process for the developers, and understanding innovativeness has formed, and continues to form, a critical management challenge internal to the project.

The second challenge was related to presenting innovativeness: what the developers considered as technical innovativeness was by outsiders easily perceived as deviance adding complication to the project. The project could only begin to find appropriate kind of support when novel solutions were accompanied with respective market, organizational, environmental and conceptual insight that enabled customizing innovative framings for targeted audiences. How to present innovativeness and deviance thus formed another critical challenge for the advancement of the project. The experience of reconstructing the history of the LMP indicates that many actors in such a project—innovators, associates, investors, managers—lack, almost chronically, the means to clarify the pros and cons of alternative framings, development paths and next steps to be taken. Certainly, they were after finances, resources, advancing their own careers, et cetera, but insofar as the project was concerned all these calculations necessarily involved continued estimations of the innovativeness and deviance of the project—both as a source of potential revenue as well as a source for potential difficulties.

The LMP case thus indicates that knowledge about the way in which a particular invention is radical or competence-enhancing or destroying *can only* accumulate gradually in some projects. In this light, retrospective analyses—whether utilizing innovation typologies or the concept of disruptive innovation (Christensen and Raynor, 2003), or SNM and transition analyses (Ende and Kemp, 1999; Geels, 2002)—by default portray breakthrough innovation projects with unrealistic clarity regarding what the project and its implications will turn out to be. This may appear as a mere stylistic choice or a matter of convenience. To us, leaving this 'fog of innovation' aside appears more consequential, akin to neglecting the 'fog of war' in military operations.

Let us examine the implications the fog of innovation has for the three literatures on breakthrough innovation we outline in the introduction. In the management of disruptive innovation, Christensen and Raynor (2003, pp. 49–50) prescribe an easy protocol, "a litmus test", for testing the disruptive potential of an idea. However, in the case of technologically discontinuous inventions it can be far from evident where the *locus* of substitution and disruption should be when the development is still ongoing. The disruptive business case cannot be induced or tested before follow-up inventions and accumulation of understanding of the technology have taken place, for these have decisive effect also on its potentials in the market, organizational and environmental dimensions. In the LMP case, the Oxidizer success was followed by the strategy of developing an LMP-based artefact or artefact sub-system for clinical laboratory use and wait for its revolutionizing potential to be actualized gradually from there on. This was rational evaluation at the time. The disruptive idea of bypassing the centralized laboratory would have been science fiction before the Internet, cheap lasers, and a thorough understanding of the present business logic and quality assurance practices were available. Indeed, reaching a point where a 'litmus test' of disruptiveness can be reliably done can require years, even decades, as it did in the LMP case.

The second set of approaches to breakthrough innovation concerns strategic niche management and transition analysis (Hoogma et al., 2002; Geels, 2004; Geels and Schot, 2007). The case analysis underscores Geels' plea for 'an actor-oriented approach working "from the inside out"... look[ing] at how actors try to navigate transitions, how they develop visions and adapt them through searching and learning' (Geels, 2004, p. 43) to complement the structuralist multi-level perspective (MLP). Indeed, the MLP could offer little for the LMP before the present date. An outside analyst could have stated the obvious about the potential for regime change in clinical chemistry—technology was stagnant and the key interest groups have interlocked interests—but the loci and dimensions of innovativeness in the LMP's confrontations with the clinical chemistry regime were unknowable before the technology was advanced to its early to mid-1990s state. However, during the last 5 or so years when the technological and business implications of LMP technology have become clearer, an analyst could define several niches that offer some, and could perhaps be made to offer more, protection for the LMP and also hold potential for a broader transition. Point-of-care testing in remote locations and quality assurance procedures are not likely to be the only ones here. We are hence inclined to conclude that for instance transition descriptions and the formation of protective niches would become truly relevant to the innovating actors only after much of the fog surrounding the project's innovativeness and its relation to the regime has already cleared. At this point many of the most decisive and vulnerable moments in developing an alternative technological pathway have already passed. We cannot know if Geels had this in his mind in his statement about the need for a complementary actor perspective, but the gestation and early development phases of potential breakthrough projects would seem to a benefit from a different management approach. More exactly, the LMP case suggests that approaches to proactive periodic evaluation could indeed provide a complement to SNM rather than a competing set of means for management challenges that emerge after the earliest and foggiest phase (cf. Hommels et al., 2007).

This brings us to the last set of literatures which we wish to engage with this paper. Socrobust and ESTEEM have taken STS-originated PROTEE ideas of turning high uncertainty to known complexity considerably further in terms of involving multiple stakeholders and in terms of the implementability of the evaluation procedure. They have also provided more sophisticated ways to assess the relationship between the project and context (Jolivet et al., 2008, pp. 30–35). Yet, even though 'de-scripting' the project, including its core, can be considered a major original insight in PROTEE (Jolivet et al., 2003), its means have enjoyed little further development in Socrobust and ESTEEM in comparison to the other parts of the evaluation process. While we have here analyzed the ongoing case retrospectively, we argue that systematically exploring the innovativeness—here done through elaborating its degree, dimensions, locus and tightness of connections—presents a way that could be used to better characterize what is possible and what would be desirable with respect to shifts in the nature of the system-to-be. This, as PROTEE argues, can help to analyze the implications of the innovation's alternative framings for different stakeholders and vice versa. Yet, clarifying the innovativeness and its likely implications requires a great deal of domain knowledge that takes years to accumulate, and hence active network collaboration with for instance, as in the case studied, lead-users and other strategically positioned actors is vital in complementing whatever 'innovation coaching' is to take place (cf. Von Hippel, 2005; Lettl et al., 2006; Poti et al., 2006a,b).

While the innovativeness and deviance of a breakthrough project is impossible to determine for certain as long as the project continues to shift, apt means to clear some of the fog appear to be urgently needed. Such means could well have helped the LMP developers to see already in the 1990s that the key issue was not how to integrate the LMP into existing analyzer functions, but to rethink the requirements and consequences of the full automation of chemical analysis—as well as to argue such a case more poignantly to patrons and investors. Further research on the strategic options of ongoing breakthrough projects just may be more urgently needed than the present literature expects—we know mostly of success stories and little about on-going projects and failures that might not have failed with more adequate measures taken.

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Manuscript 1: Höyssä, Maria. Knowledge types, scientific research and technological development

KNOWLEDGE TYPES, SCIENTIFIC RESEARCH AND TECHNOLOGICAL DEVELOPMENT

Abstract

This paper develops a framework of the different types of research-based knowledge that can be involved in technological development. The framework identifies types of knowledge dispositions, types of propositional knowledge, and types of skill, or procedural knowledge. The framework contributes to the research on the science-technology relationship by enabling a qualitatively more informed understanding of the nature of scientific knowledge creation and its transfer from universities to industries than has been possible with the hitherto existing conceptualizations. First, it differentiates between the propositional knowledge types related to scientific observations, explanations, inventions and applications. Second, it introduces methodological research skills as a form of procedural knowledge which is important but often overlooked in the existing typologies of scientific knowledge. Third, it establishes that the creation of applicable knowledge is always related to specific instrumental principles. These notions are used to clarify specific issues in the discussions on the university-industry knowledge transfer and the linear vs. interactive models of innovation.

Keywords: Knowledge types, scientific research, technology, invention, innovation

III

1. Introduction

In this era of knowledge-based economic development, policy-makers around the world are hoping to unlock the full potential of universities by aiming to facilitate the flow of science-based knowledge from universities to industrial innovation. However, the evidence of success is mixed: generally, the policies to stimulate innovation appear to be based on an emulation of the policies of a few well-to-do regions, and the effectiveness of such solutions remains ambiguous (Miner et al. 2001; Mowery and Sampat 2005). The situation calls for further research to better understand how knowledge creation in universities relates to industrial innovation. It has been suggested that to gain further understanding of this phenomenon, the influence of the *context* of the knowledge transfer should be better understood (Bercovitz and Feldman 2006; Miner et al. 2012). This paper advocates the view that to gain an in-depth understanding of the role of universities in innovation in a context-sensitive way, we also need a qualitative understanding of the types of research-based knowledge that are potentially transferred between scientific research and the industrial development of technologies.

The need for a fresh perspective on the university-industry knowledge relations is prompted by the observation that pre-existing conceptualizations only paint a blurry picture. On the one hand, the *place of university research in the innovation process is not always the same*. The controversy between the "linear" (Bush 1945; Nelson 1959; see also Arrow 1959) and the "interactive" (Kleine and Rosenberg 1986) models of innovation is dissolving into the view that innovation processes may involve both "linear" and "interactive" features (Balconi et al. 2010; Pavitt 2005). University research may be involved in any stage of the innovation process and is equally likely to initiate innovation projects as to contribute to their completion (Cohen et al. 2002: 4). Even the *direction of the knowledge flow* with respect to innovation cannot be taken as given, for scientific research may also be inspired by technological development, and this may happen either in the academic or the industrial context (Brooks 1994; Rosenberg 1990).

On the other hand, *it is unclear what universities actually contribute to the innovation process.* The generic answer is "knowledge". However, research on knowledge and technology transfer often describes knowledge flows as quantifiable indicators, such as patent citations or licenses (Henderson et al. 1998; Mowery and Ziedonis 2001; Rosell and Agrawal 2009). This leaves unaddressed the precise nature of the knowledge beyond its indicators, as well as any potential other kinds of knowledge that are less quantifiable. Efforts have been made to study a broader range of channels of transfer between universities and industries. However, the nature of the knowledge actually flowing through them is rarely specified. For example, do such diverse "channels" as the student recruitment, conference participation, and patent licensing really represent different instances of the transfer of the same "knowledge substance" (Bercovitz and Feldman 2006; D'Este and Patel 2007; Gilsing et al. 2011; Schartinger et al. 2002)? The different channels imply different *kinds* of knowledge. Some typologies have been developed to capture different kinds of knowledge (Bekkers and Bodas Freitas 2008; Cowan et al. 2000; Faulkner 1994; Lundvall and Johnson 1994; Zellner 2003). While they illustrate that knowledge should not be treated as a single category, these typologies do not specifically discuss the ways in which different types of scientific knowledge may—or may not—be related to the development of technology.

This paper seeks to identify different types of scientific research knowledge in order to conceptualize relations between scientific and technological development in the context of natural and medical sciences. It draws on the earlier attempts at identifying types of knowledge and types of scientific research, as well as on the research mapping the broader contributions of science to technological innovation. This results in a view where scientific research is:

- driven by Aristotelian dispositions towards empeiria, episteme, phronesis and techne
- practiced through analytical, methodological, inventive and application skills
- producing theoretical, empirical, instrumental and applicable knowledge

The linkages between the different aspects of scientific knowledge and the development of technology are elaborated with the aid of Arthur's (2007) definition of invention, which shows how the knowledge of natural effects is combined with practical human purposes. The framework is useful, first, in highlighting the importance of methodological research skills for both technological and scientific progress. Second, it differentiates between knowledge related to scientific discovery and knowledge related to invention. Third, it establishes that the creation of applicable knowledge is always related to specific instrumental principles. The resulting approach can be further used to diagnose what is actually transferred when "knowledge" is transferred and what the division of labour is in research and development activities in specific organizational, industrial or spatial contexts.

The paper is structured as follows. The following, second, section provides a critical reading of some prior typologies of knowledge in the literature on the nature of scientific research. It then introduces the Aristotelian "dispositions toward knowledge" in order to identify the different types of scientific knowledge. Finally, it distinguishes between embodied *research skills* vs. explicit (propositional) *knowledge*. The third section integrates the different types of disposition, knowledge and skill into a coherent approach, which captures the different ways in which knowledge can relate to technology development. The fourth section discusses the implications for understanding knowledge flows in university-industry relations. The fifth section concludes the paper by summarizing the novel features of the present approach.

2. The dimensions of scientific research and knowledge

2.1 Different conceptions of knowledge

Different typologies have been created to improve the understanding of knowledge. Faulkner (1994) lists five types of knowledge used in industrial innovation. These are categorized according to the object of knowledge, each with several sub-categories: knowledge related to the natural world; to design practices; to experimental R&D; to the final product; and, finally, to knowledge itself (i.e. the location and availability of external knowledge and research facilities). Additionally, Faulkner notes the further dimensions of knowledge as to be understanding—information—skill; codified—tacit; complex—simple; local—universal; specific/contingent—general/meta-level. Lundvall and Johnson (1994) have proposed a taxonomy of knowledge consisting of know-what, know-why, know-how, and know-who knowledge, which has been suggested as useful for understanding the differences in the creation, distribution and use of knowledge at the national level (Lundvall 1998) as well as performance at the level of firms (Jensen et al. 2007). Malerba and Orsenigo (2000) seek to explain the direction of innovation and industrial evolution by differentiating between knowledge and competences, and by discussing knowledge along the dimensions of accessibility, cumulativeness, technological regime, domains of knowledge (concerning technology or demand) and complementarities. Further, Gorman (2002) has proposed a division into knowledge types of information / declarative knowledge (what); skills / procedural knowledge (how); judgment (when); and wisdom (why) as being helpful in explaining the tacit component of technology transfer, especially within teams. Asheim and Gertler (2005) have differentiated between analytic and synthetic (and symbolic, Asheim and Mariussen 2003) industrial knowledge bases in order to emphasize how the nature of innovation and development activities is shaped by the underlining knowledge typical of the industry. These conceptualizations look at knowledge from the perspective of technology development in the industrial context rather than from the perspective of scientific research in universities. While they highlight some properties of knowledge that are relevant also for the present paper, they do not elaborate on *what kinds of scientific knowledge* are relevant to technology development.

There have been several attempts to capture the—at times intimate—relationship between scientific knowledge creation and the development of practical applications. The layman distinction between basic knowledge as “disinterested” and applied research as “application-oriented” has been criticized as unclear. De Solla Price (1984) claims that basic science should be defined as studying the world of nature and applied science as studying the world of the artificial, or technology. Donald Stokes (1997), in turn, argues that “basic” and “applied” research are not the opposite ends of the continuum; research can be driven *both* by the quest for fundamental understanding *and* by the considerations of use (Figure 1).

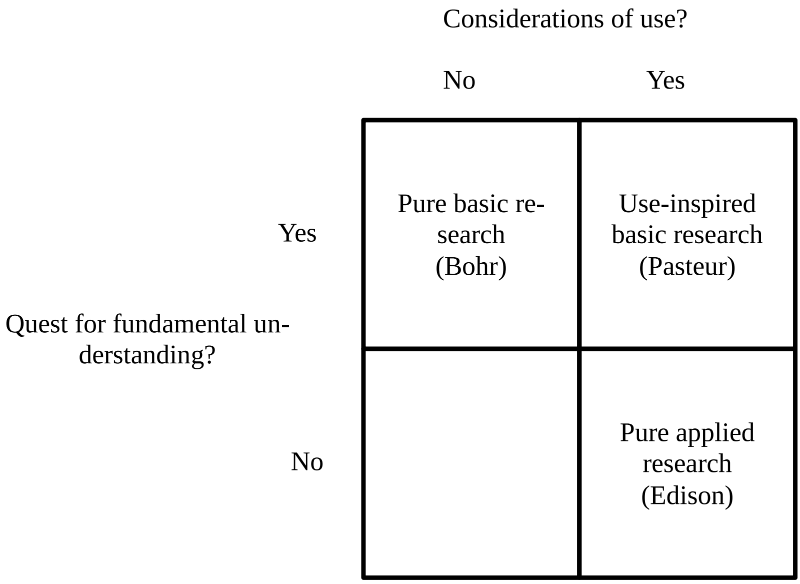

Figure 1 The quadrant model of scientific research (Stokes 1997, 73).

Stokes’ approach reveals that the nexus between science and technological innovation is formed when new knowledge creation occurs simultaneously with considerations of use (see also Mokyr 2002). Nelson (2004, 459) finds this kind of a double-purpose inherent in “specialized fields of applied science or engineering developed out of the experience of more generally trained scientists working on the problems of a particular technology or industry”, such as metallurgy, electrical engineering, computer science, immunology and cardiology. Boon (2006) pinpoints specific kind of knowledge that forms the science-technology nexus: “knowledge that consists of scientific explanation of physical phenomena that occur in—or that are produced by—technological artefacts” (ibid., 34). This is an important insight concerning engineering sciences. Its significance in the contexts of the biological and medical sciences, where the distinction between man-made artefacts and natural organisms is harder to make, remains to be established.

Even though one could think that the studies of knowledge transfer from the university context to industries involve a sophisticated understanding of the kinds of knowledge that are transferred, these studies mostly identify *ways* of mediating knowledge rather than *types* of actual knowledge. E.g. Gilsing et al.

(2011) focus on the channels of this transfer; Schartinger et al. (2002) on the types of interactions through which knowledge is transferred; and Bercovitz and Feldman (2006) on the types of transaction through which knowledge is transferred. As an exception to the rule, Zellner (2003) distinguishes between actual types of knowledge—scientific skills, propositional knowledge and technicalities—and divides these into non-specific and specific forms. However, Zellner's knowledge types are conceptually related only to basic research and do not discuss the more applied forms of public research. Thus his typology cannot be taken as an all-inclusive approach to scientific knowledge.

What Zellner (2003) did, however, was to distinguish the knowledge which is related to scientific methods and techniques as a separate type of knowledge. Apparently, this had not been done until then, even though the significance of new scientific methods, techniques and instruments (such as the telescope, voltaic electricity, nuclear magnitude resonance and recombinant DNA) for industrial development had already been firmly established (e.g. Rosenberg 1992; Shinn and Joerges 2002; Solla Price 1984; see also Baird 2004; Shinn 2005). Zucker and his collegues (Zucker and Darby 1996; Zucker et al. 1994) had shown how knowledge of the new techniques of genetic recombination was absolutely crucial to the commercial application of the related new biological discoveries. Also Brooks (1994) had included new methods, laboratory instruments and analytical as well as simulation techniques when pointing out the important contributions that scientific research has made to technology development (for a similar argument, see Salter and Martin 2001).

Summing up, while multiple attempts have been made to characterize the different kinds of knowledge, the types of scientific knowledge, and the nature of knowledge at the science-technology interface, none of these approaches makes a systematic synthesis of the types of knowledge that scientific research may feed into technology development. The synthesis should recognize the fundamental knowledge of nature, the knowledge of technologies, the synthesis between natural and technological knowledge, the considerations of use, as well as the scientific research skills and methods used in technological development.

2.2. The Aristotelian dispositions towards knowledge

Interestingly, a multi-dimensional conceptualization of knowing, which embraces the aspects of knowledge outlined above, can be found already in the writings of Aristotle. A few of the authors mentioned above have referred to some Aristotelian concepts (cf. Asheim et al. 2011; Gorman 2002; Johnson et al. 2002; Lundvall 1998; Mokyr 2002), but without utilizing them in a systematic way. A more systematic utilization would require recognizing that, in his texts, Aristotle describes ways of knowing rather than types of knowledge. Aristotle's concepts can, however, be used to develop a framework to identify distinct types of knowledge and to see how they relate to each other.

Aristotle uses the word *hexis* to capture different personal qualities, including ways of knowing. *Hexis* is often translated as 'virtue', a special kind of "disposition" (Hutchinson 1986). Aristotle defines five "virtues of thought": *technê* (most often translated as 'craft/art'), *epistêmê* (the knowledge of context-independent unchanging certainties, often translated as 'scientific knowledge'), *phronêsis*[1] (practical wisdom/prudence), *sophia* (theoretical wisdom), and *nous* (intellect) (Aristotle *Nicomachean Ethics*; Parry 2008). Of the five virtues, especially the notions of *episteme* and *techne* have in later research been seen as relevant for scientific and technical pursuits (e.g. Johnson et al. 2002; Mokyr 2002), and these antique expressions still feature in the English language when one refers to epistemology or epistemic and technology or technical. According to Parry's (2008) interpretation of Aristotle, *episteme* concerns the knowing of that which "is always or for the most part" (Parry 2008, quoting Aristotle's *Metaphysics*, IV,1027a20)—meaning the knowledge of mathematical necessities as well as of the less strict laws and regularities of nature. "*Technê* is a disposition (*hexis*) that produces something by way of true reasoning; it is concerned with the bringing into existence (*peri genesin*) of things that could either exist or not." (Parry 2008, quoting *Nicomachean Ethics*, VI.4,1140a1-20).

When applying Aristotle's concepts, it should be remembered that his view of knowledge differs from the modern scientific quest: it does not involve experimentation (Parry 2008). According to Aristotle, the intuitive reason of the individual, *nous*, grasps the first principles upon which *episteme* can be built on (ibid., VI.6,1140b). The problem is that Aristotle does not seem to link this intuitive reason to perception through the senses, which makes the concept unsuitable for characterizing the principles of modern natural science. And *sophia* builds on *nous*; it is wisdom that arises from knowing the truth of the first principles and what follows from them, in other words, a combination of *nous* and *episteme* (ibid., VI.7,1140b). As *nous* and thus also *sophia* overlook observation as the basis of knowledge, these concepts are less compatible with and less cited with respect to modern research, and are therefore not utilized when building the present framework. However, Aristotle does not entirely ignore the role of observation. He calls the forming of beliefs based on repeat-

1 For simplicity, the accent marks belonging to the original Greek words technê, epistêmê and phronêsis are not used in the rest of the paper, except when they occur in quotations.

ed perception and memory *empeiria*, and sees it as facilitating further inquiry (Butler 2003). Aristotle does not give *empeiria* the status of virtue, but regards it as one of the lesser dispositions; even animals learn by repeated perception and memory (*Posterior Analytics*: II,19). Nevertheless, considering the significance of empirical research (field and laboratory research, experiments, and the instruments of observation and measurement) for the scientific inquiry of today, this paper argues that it is justified to consider the lesser disposition of *empeiria* (instead of *nous* and *sophia)* as one of the dispositions driving knowledge creation in scientific research.

The disposition towards *episteme* can be said to correspond to the “quest for fundamental understanding”, as described by Stokes (Figure 1). However, *techne* is not equivalent with the “considerations of use”, the other knowledge creation dimension recognized by Stokes. The present paper argues that when applied in the context of modern scientific research, the craft or art described by *techne* should be taken to refer to the craft aspect of science. It encompasses the use of concrete techniques and instruments to observe, produce, simulate and manipulate natural phenomena. The “concrete things” that are brought “into existence by way of true reasoning” are the experiments, effects, observations, data and documentation of natural phenomena. Sometimes even the tools of the craft—the scientific instruments—are crafted as part of the research. *Techne* is thus of outmost importance to the methodological expertise of science. It concerns *how* to accomplish things, but does not extend into judging the *purposes* of these things.

For expressing the purposeful aspect of knowing, Aristotle’s *phronesis* is the appropriate disposition. It stands for the “true and reasoned state of capacity to act with regard to the things that are good or bad for man”, producing “judgments about what is to be done” (*Nicomachean Ethics*, VI.5,1140b). According to Aristotle, *phronetic* knowing is “concerned not only with universals but with particulars, which become familiar from experience” (ibid., VI.8,1142a). Thus *phronesis* is the ability to make a diagnostic assessment of what should be accomplished, drawing on prior experience of what is, why it is like that, and how to change it. Such an assessment is inherently value-based. It represents the “ought to”, “should” and “could” type of conviction. It is argued here that this knowledge disposition can be taken to equal “considerations of use”, as described by Stokes (1997). For example Louis Pasteur’s approach to research—simultaneously developing of a germ theory and searching for ways to preserve milk—can be seen as involving both *episteme* and *phronesis* (compare with Figure 1). However, it is obvious that also the *techne* and *empeiria* of experimenting with microbes and foodstuff must be relevant for the same research, even if these dimensions of knowing do not feature in Stokes’ (1997) argument.

To sum up, scientific knowledge creation can be regarded as driven by four knowledge dispositions: *episteme*, *empeiria*, *techne*, and *phronesis*. While on the first glance it may seem that *episteme* and *empeiria* would be exclusively related to “basic” science, and *phronesis* and *techne* only to “applied” research and innovation, such a separation should not be made. Even if some of the above outlined four dispositions may feature more frequently in studies of nature than in studies of the artificial, or vice versa, any disposition may, in principle, be involved in both kinds of studies. For example, the practice of a technical craft may produce surprises that give rise to questions belonging to other dispositions: What happens here? Why does it happen this way? Should it be prevented or utilized? Thus, extending the idea of Stokes (1997; Figure 1, upper right quadrant), knowledge dispositions do not have to be mutually exclusive, as they can and often do co-exist. This way of understanding research allows a scientific explanation to either precede or follow technological development; both sequences are known to occur in the real world (Balconi et al. 2010; Rosenberg 1990).

2.3. Knowledge and skill

Scientific knowledge has also been categorized according to whether it concerns the world itself or the way we operate in it. Science produces propositional knowledge, which is broadly understood as a justified true belief (Audi 1998) or “knowing that” (Ryle 1949). This kind of knowledge concerns the world. But the making of science also involves procedural forms of knowledge (Sahdra and Thagard 2003), namely the “knowing how”, or skills (Ryle 1949). To simplify, in this paper, the procedural knowledge of the scientists is called research *skills*. The term *knowledge* is used only in regard to propositional knowledge.

The distinction between *knowledge* and research *skill* is related to the well-known distinction between explicit/codified and tacit knowledge (Polanyi 1966, 20-25; Cowan et al. 2000; Johnson et al. 2002). (Propositional) knowledge can be made explicit and codified. This knowledge can be considered as the output of research, which is often also published. Research skills are embodied personal abilities to carry out various cognitive and tangible procedures. Skills are part of *knowing* rather than of knowledge. Skills can, to some degree, be described verbally or in written form, as in handbooks or in the methodology sections of empirical papers. Still, learning the description of the skill is not the same as to have the skill. Actual skills need to be learned through experience. This learning has a tacit basis in our innate cognitive tendency to recognize patterns and similarities (Nightingale 1998; Sahdra and

Thagard 2003). The ability to understand the meaning of codified knowledge, to interpret it in the proper context, is also a skill with such a tacit basis. Thus, in this paper, “knowledge” refers to explicit statements, whereas “interpreting” and “applying” knowledge refers to personal skills. There is no “tacit knowledge”, only “tacit knowing”.

There are different levels of mastering a skill. A true expert, according to Flyvbjerg (2001), has practiced her skills in different contexts so thoroughly that her pattern-matching ability has become intuitive and tacit so that it extends far beyond mere rule following (Flyvbjerg 2001). Sahdra and Thagard (2003) show how such expertise is required in molecular biology research, and that scientific experts integrate propositional knowledge and procedural knowledge—that is, knowledge and skill. It can be concluded that research skills and basic disciplinary knowledge are learned through basic scientific training, and the ability to integrate them in order to produce new knowledge accumulates gradually through research experience.

3. A novel approach for understanding scientific knowledge creation

3.1. Connecting disposition, knowledge and skill

The four Aristotelian dispositions to knowing can now be used to differentiate between various kinds of research knowledge and skill. The four research dispositions—*episteme* (the understanding of laws and regularities in nature), *techne* (the craft to make things into being), *phronesis* (practical wisdom about the desirable courses of action) and *empeiria* (repeated observations as the basis of beliefs)—characterize a researcher’s alternative approaches towards natural phenomena. Any phenomena can be approached from the point of view of any disposition. It depends on the researcher’s personal interests as well as on the disciplinary and other institutionalized traditions which dispositions are emphasized in the specific research processes. In Figure 2, the four dispositions are represented by the four forked arrows pointing inwards into the research process, which is represented by the oval shape.

The outward-pointing arrows denote the propositional and mostly codified results of the knowledge creation process: the different types of research knowledge. It is proposed that each type of knowledge arises from the combination of the two “surrounding” (in Figure 2) research dispositions. *Empirical knowledge* arises from the efforts to answer both the question of what is and how, then, to craft the proof for it. This knowledge consists of the reported observations or data concerning natural phenomena and their effects. *Theoretical knowledge* arises from the efforts to answer both what is and which regularities of nature explain it. This knowledge concerns the explanations of natural phenomena and effects: novel facts, models, theories and laws. *Instrumental knowledge* arises from the efforts to answer both what should be accomplished and what regularities of nature would enable one to do that. This knowledge consists of principles of how natural effects could—in theory—be utilized to create novel technologies, methods, techniques and therapies that enable new methods of manipulating, controlling or observing nature, life or information. *Applicable knowledge* arises from the efforts to answer what should be accomplished and how to craft that something into being. This knowledge informs how instrumental principles can be put to practical use. It may, for example, concern the explanation of why a principle works, the conditions and contexts in which the principle can be made to function most reliably, or the range of problems to which the principle can be applied.

The segments of the oval centre of Figure 2 represent the embodied research skills, i.e. the abilities to generate certain types of knowledge. It is proposed that the production of observations, theories, inventions and applications each require somewhat different, but related, sets of skills.

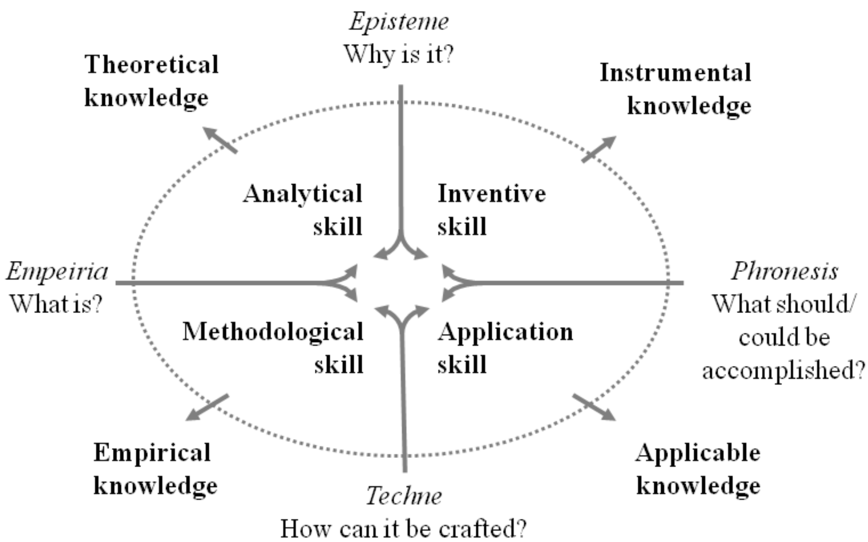

Figure 2 Types of knowledge, skill and disposition in scientific research.

The upper hemisphere of the framework represents the research which is focused towards the abstract *episteme*. In this disposition, the purpose of the research activities is to create knowledge of natural phenomena that holds independently of the context. Epistemic knowledge is therefore easy to codify.

The lower hemisphere of the framework represents the research focused towards the hands-on *techne*. Here, the purpose of the research activities is to experimentally study and control natural phenomena, and to craft observations, effects and/or techniques that enable this. Due to the variability in material contexts, codification tends to be used more for concrete, descriptive content than for abstract, theoretical content. The left hemisphere represents the research focused towards *empeiria.* The purpose of the empirical research activities is to grasp knowledge of natural phenomena through repeated observations and experience. The right hemisphere represents the research focused towards purposeful, value-laden *phronesis* that seeks to engage with the world and solve practical problems by utilizing natural phenomena. Here, the considerations of use, i.e. the practical implications and applications of research or acting upon those implications, guide the process of knowledge generation.

The different research skills are interdependent. They are connected through different types of background (propositional and procedural) knowledge of the individual, or within the research team. For example, theoretical understanding backs up empirical research, as the choice of representative samples or cases requires that the research problem be well defined. The process of inventing relies on the empirical and theoretical knowledge of the natural effects that may be utilized in the invention. The ability to create applicable knowledge, in effect, means an ability to customize other research skills for the study of how some specific purpose can be reached. This interdependence means that individual research skills cannot be strictly defined.

In this paper it is proposed, however, that for analytical purposes it is useful to label the following broad categories of skill. *Analytical skill* underlies the theoretical knowledge creation. It involves framing problems, formulating questions and posing hypotheses by building on what is theoretically known of natural phenomena as well as on what has been empirically observed, and codifying the results in a form which is understandable by the relevant others.

Methodological skill underlies the empirical knowledge creation. It involves the use of scientific techniques, experiments and instruments to find, measure, simulate and control natural phenomena and effects. A methodological skill is practiced to produce observations in a systematic way that best allows the practice of a particular analytical skill, and to codify these observations into empirical knowledge which can be used to prove and further test the validity of the explanation. Methodological and analytical skills combined drive discovery, the "unearthing of a fact or a natural law that existed all along but that was unknown to anyone in society" (Mokyr 2002, 12).

Inventive skill underlies the instrumental knowledge creation. It relates to the carrying out of a process in which some purpose or need is linked to an effect that can be exploited to satisfy it. This process of invention "proceeds from a need for which existing methods are not satisfactory, which forces the seeking of a new principle (the idea of an effect in action); or from a phenomenon or effect itself—usually a freshly discovered one—for which some associated principle of use suggests itself" (Arthur 2007, 275). Inventive skill is needed to come up with this new combination. For example, the principle of radar was discovered when its developers realized that one could detect approaching enemy aircrafts by utilizing the effect that radio waves are reflected from metal surfaces (Arthur 2007). Invention may involve a discovery, but the two are different: discovery concerns nature, invention concerns a means to achieve certain ends. These may be the two sides of the same coin, however: for example "[t]he discovery of insulin as a cure for diabetes was an important contribution to science, owing to the intrinsic interest of its subject matter; it was also the invention of an operational principle serving to cure diabetes" (Polanyi 1962, 178). Discoveries belong to the public domain, whereas inventions are often patentable. Patenting relates to the codification aspect of inventive skill; patent databases are places where instrumental knowledge accumulates.

Application skill underlies the applicable knowledge creation. It concerns putting instrumental principles into practice. In other words, it produces knowledge that is needed for creating, manipulating, engineering, reinforcing, changing, diagnosing or healing material or living things. The application skill applies the other research skills to increase the knowledge of the phenomena underlying the functioning of the instrumental principle, thus reducing the need for "blind" trial-and-error experiments in the innovation process. The application skill may involve theory-building and simulation, but usually real world problems contain so many contextual variables that also empirical experiments are needed to map the systemic interactions between the parts (or organs) of the research object as well as between the object and its environment. The codification of the resulting knowledge may range from scientific publications to technical blueprints. However, the application skills do not only lead to codified applicable knowledge. They may also involve applying knowledge directly: putting knowledge to action through the prototyping of new entities or processes or the improving of existing devices, materials, organisms, substances, reactions, etc.

Prototyping, i.e. demonstrating the instrumental principle in action, ends the process of invention (Arthur 2007) and the related formulation of the instrumental principle. This process may occur rapidly, but it may also take years or decades, in which case the difference between basic and applied research can remain ambiguous for a long time. For example, the *phronetically* oriented search for a cure for cancer seeks to find a biological effect that could, for example, support the immune system to fight cancer, use chemotherapy to destroy cancerous cells, or use tumour suppressor genes to restore normal growth in cancer cells—each approach representing a different potential principle. Such research is likely to be a process of iteration between different knowledge dispositions: prior knowledge, new empirical observations, hypothesizing about the mechanism of a potentially suitable effect, testing, re-framing or changing the hypothesis, developing the methodology, doing more empirical observation, verifying the mechanism of the effect, proposing an instrumental principle of how the effect could be used, tentative operationalization of the principle, rejection or verification or re-framing of the principle, more solid operationalization and more solid testing and re-framing, etc (for a cognitive model of the nature of such iteration, see Nightingale, 1998). This process continues until a fully fledged instrumental principle potentially emerges and can possibly be patented and commercialized. Invention may also be accompanied with scientific discovery. However, more important than distinguishing precisely between "basic" and "applicable" knowledge is simply understanding the role of natural effects for instrumental knowledge and the role of instrumental knowledge for applicable knowledge.

3.2. The dynamic relation between the elements

Let us now illustrate this approach by imagining a sunny day thousands of years ago. A person with the disposition towards *empeiria* observes the phenomenon that the sun appears to move in the sky at a steady pace, which constitutes the passage of the day. She becomes aware of the effect that the shadows of inert objects also move at the same pace. She tries to explain the phenomenon of the moving sun by deducing that the sun travels around the earth. Thus, she creates (in this case, incorrect) *theoretical knowledge*. Her *phronetic* disposition prompts the idea that the time of the day could and should be measured more precisely by other means than by directly observing the position of the sun. This (imagined) person has some *inventive skill*, and thus comes up with a new principle: the effect of a shadow's steady movement across the ground surface could, in combination with a correctly positioned even grid, be applied to make a sundial. This principle represents *instrumental knowledge* (other principles of time measurement have later outlined the hourglass and also pendulum-, spring- and quartz-based clockworks). The construction of a sundial represents the researcher's *application skill*; the sundial itself represents applied knowledge*;* a drawing or explanation of how to construct a sundial represents *applicable knowledge* (the need for applicable knowledge generation before the construction would, however, be more pressing in the case of the quartz-based principle of time measurement). Should the researcher have the *methodological skill* to make more systematic celestial observations and have better *analytical skills*, she might have proposed, as Copernicus did, that the earth rotates instead of the sun circling it (*theoretical knowledge*). This, and further astronomical discoveries would have been facilitated had the researcher been able to boost her *methodological skill* with new instruments, based on new *instrumental knowledge, as* Galileo did with the telescope. With suitable instruments, Galileo was able to create new *empirical knowledge*: he saw, for instance, that Venus had phases. This new discovery, in turn, suggested a new piece of *theoretical knowledge,* that Venus is illuminated by the sun—which resolved some hitherto unsolved problems in the Copernican astronomy (de Solla Price 1984, 8).

The above notions illustrate the interplay between the four types of disposition, knowledge and skill. The schematic description of these relations seems to suggest a sequence of events which is essential for the emergence of new techniques, discoveries, theories and applications. But there is no overarching, determined sequence or direction of knowledge transfer or transformation between the various types of knowledge and skill (the round or cyclical rather than sequential shape of Figure 2 also emphasizes this). Sometimes new understanding of natural phenomena springs forth from the study of problems of the existing technologies, and the transfer of knowledge goes from industry to science (Brooks 1994). Rosenberg (1990, 169) describes how the improving of steam engines led to the discovery of the principles of thermodynamics, and how the fixing of the static noise issue in radiotelephony service gave birth to the discipline of radio astronomy. Sometimes research focuses on natural phenomena but is still strongly application-oriented, as in the discovery of the pasteurization technique (Stokes, 1997). Sometimes research focuses on technological principles in order to advance science, as did the research leading to the development of the ultracentrifuge (Shinn and Joerges 2002). And, at other times, new technology springs forth from the study of natural phenomena in quite a “linear” sense. There may appear to be only little delay in the associated knowledge transfer from research to application, especially in the fields where the object of research is “technological” and the theory (*episteme*) and art/craft (*techne*) of the field go intimately hand-in-hand, as they do in pharmacology, biotechnology, nanotechnology or materials science.

Sometimes, however, there is a delay of decades before a particular scientific discovery is approached from the *phronetic* perspective of need, if at all: For example, the physicists Pierre and Jacques Curie found the piezoelectric effect of quartz in their university laboratory in 1880 (Amy 2005), but it was only applied to a practical problem thirty-two years later, possibly inspired by the sinking of the Titanic. The accident triggered the research on underwater detection systems, shortly followed by the actual sonar applications, one of which applied the piezoelectric effect (Apte 2002, 981-982). As Polanyi argued already over fifty years ago (Polanyi 1962), a short-sighted emphasis on science where the applications can be envisioned beforehand is likely to stall both scientific and technological progress. An effect or principle that once originated in science and was, at first, without immediate use may yet spread not only to just one industry, but from that industry to others. This happened, for example, when the use of the piezoelectric effect spread to ultrasound devices in medicine, ballistics, biomechanics, and engine testing during the 20th century (Amy 2005). Among other things, piezoelectricity is presently used in sensors and actuators in many industries. Some of these industries may have little contact with the present front of scientific research, such as mechanical engineering. In these cases, the industry may have little need for university-generated knowledge—and still have ample need for *skills* in the latest research, simulation and modelling techniques (Pavitt 2005, 93).

4. Implications for research at the university-industry interface

4.1. Knowledge transfer

By integrating very different forms of research-based knowledge in a coherent framework, the present approach paves the way for a more holistic understanding of *what kind of knowledge universities contribute to technological development* (as depicted in Figure 2).

Research dispositions represent a researcher's point of view on natural phenomena: research topics and approaches. They indicate what kind of knowledge and skills s/he is interested in developing and why. *Understanding the various research dispositions* helps parties with complementary competences and interests find each other. Knowing someone's research dispositions is a science-specific form of "know-who" knowledge, "information about who knows what and who knows what to do" as defined by Johnson et al. (2002, 251). Some information concerning research dispositions is revealed by scientific publications, but a deeper understanding of potential mutual complementarities is best created in face-to-face situations, such as conferences and meetings. Research dispositions contribute to innovation when the encounters between the different dispositions of one researcher or a group of researchers enable the creation of novel answers to the two crucial questions underlying innovation processes: what is needed and what is possible (Stefik, M. and Stefik, B. 2004).

Research skills represent the abilities to generate certain types of knowledge. Skills are embodied and thus gained through practice. Therefore also the transfer of skills is strongly dependent on the interaction between people. Especially in the cases of context-dependent methodological and application skills, it is likely that the transfer of skills is strongly dependent on the interaction in particular research sites and settings, such as laboratories, where the material/technical aspect of research is performed. Such proximity dynamics have formerly been more exclusively associated with industries with a "synthetic" knowledge base, relying on the practices of engineering, rather than with industries with an "analytical" knowledge base of codified science (Asheim and Gertler 2005). However, science-based innovation projects have been found to switch between the analytical and synthetic modes (Moodysson 2008; Moodysson et al. 2008). By presenting research skills and (propositional) knowledge separately, the suggested approach offers a more fine-grained conceptual toolset for analyzing what kind of knowledge creation is taking place in the different phases of the research that underlies science-based innovation.

Research knowledge represents the outputs of research. For example, Cohen et al. (2002, 8-9) have previously divided public research outputs into "research findings", "prototypes" and "instruments and techniques" when studying how manufacturing industries utilize public research. Their category of "prototypes" is partly the same as applicable knowledge: applicable knowledge creation may or may not involve prototypes—its defining feature is that it seeks to illuminate the functioning of instrumental principles. "Instruments and techniques" resembles instrumental knowledge, but the latter consists of principles rather than of concrete examples of solutions. Instrumental knowledge involves also other inventions than those which relate to scientific methods. The category of "research findings" presented by Cohen et al. (2002) groups all types of propositional knowledge together, while the proposed approach recognizes four types of propositional knowledge. Thus, doing surveys that involve a further breakdown of the "research findings" of Cohen et al. (2002) into these proposed categories of knowledge should illuminate the industrial differences in knowledge use at a deeper level. A similar breakdown would be possible, for example, with respect to Zellner's (2003) typology, which differentiates between specific and non-specific scientific skills, and between propositional knowledge and technicalities, but not between types of propositional knowledge. The approach in this paper offers a systematic way to map the different research outputs and the skills involved in the production of these outputs. Thus, it points to the possibility of diagnosing the types of knowledge and skill flows between university and industry.

Also, the proposed framework opens up a new window into the inquiries concerning how social or spatial factors enter into the knowledge transfer (as called for by Bercovitz and Feldman 2006; Miner et al. 2012). A more qualitative understanding of the nature of the knowledge being transferred enables one to choose empirical settings that display contextual variation while being as comparable as possible to the types of knowledge and skill that are cultivated in universities. One could also study the effect of external context on the prevalence of the different research dispositions and the related production of skills and knowledge types in universities. Such a study should complement the existing broader analyses on entrepreneurial universities (Feldman and Desrochers 2003; Feldman and Desrochers 2004; Bercovitz and Feldman 2006). The framework could also be used to study what kind of knowledge firms in knowledge-intensive industries base their business on. Such analyses should complement, for instance, the existing approaches for categorizing knowledge-intensive business services according to the analytical, synthetic and symbolic knowledge bases in different sectoral or territorial contexts (Strambach 2008).

4.2. The role of research methods in the science-technology relation

In the context of scientific research, an especially interesting form of inventing concerns new scientific methods. The present approach clarifies which forms the knowledge of methods can take. First of all, there are university-trained experts who have up-to-date *methodological skills* on the most recent research methods and techniques. Second, some knowledge of methods and techniques can be codified, for instance in patents and handbooks. Such knowledge is *instrumental knowledge*. Third, some knowledge of methods and techniques can be incorporated into scientific instruments, equipment and software that enhance or automate human methodological skills. Such knowledge is applied knowledge, i.e. knowledge put to action through technology. Baird (2004) has proposed a related concept, “thing knowledge”. The skill to use existing methods is not the same as the skill to envision new ones. To create a new method requires that either the problem or the means to achieve it needs to be (re)defined and solved from a new angle. This skill appears to be more prevalent among academics who are unsatisfied with the performance of existing methods than among industrial product developers (von Hippel 1976).

Prior literature has sometimes had trouble clarifying the interconnections between scientific method, discovery and invention. For instance, Thursby, J. and Thursby, M. (2011) refer to the “discoveries of entirely new methods of inventing” (606), while Zucker and Darby refer to the “invention of a method of discovery” (1996, 12710) when meaning the creation of specific techniques in biotechnology and the subsequent empirical and theoretical discoveries and further industrial applications. De Solla Price has proposed a concept of “instrumentalities” to mean the “laboratory method for doing something to nature or data in hand” (1984, 13). His examples of instrumentalities do not only involve physical instruments and methods but also mathematical techniques, such as differential and integral calculus and factor analysis. The present paper owes the concept of instrumental knowledge to the insight of de Solle Price. However, in the approach proposed here, by using Arthur’s (2007) definition of invention, the idea of instrumental knowledge is extended beyond laboratory methods to any principles that make it possible to observe, manipulate or control nature, life or information. Finally, by linking the concept of instrumental knowledge to Aristotle’s idea of *episteme*, this approach emphasizes that instrumental knowledge relies on the understanding of the regularities of nature.

4.3. Models of innovation

The proposed approach can also be used to clarify the *place of university research in the technological innovation process*, and to explain why features of both the linear and the interactive models of innovation appear to be correct, depending on the context (Pavitt 2005; Balconi et al. 2010). The crux of the matter is whether university research supplies the knowledge to ongoing innovation processes, or enables the initiation of an innovation process.

Over a third of the industrial innovation projects utilize public research to complete innovation projects (Cohen et al. 2002: 5-8). In terms of the present paper, in the latter stages of innovation development, university research is needed to create applicable knowledge. Such knowledge enables the verifying, realizing or optimizing of the known instrumental principles in practice, for instance by studying the conditions in which the underlying natural effects can best be observed, replicated, inhibited, or scaled up. Universities may also produce theoretical and empirical knowledge without any apparent connections to specific instrumental principles—yet this knowledge may, in time, come to illuminate the functioning of an instrumental principle as industrial researchers keep utilizing the available stock of knowledge in order to solve specific technical problems (Kline and Rosenberg 1986, 291). Thus, originally “disinterested” knowledge can later become part of innovation process.

Cohen et al. (2002) find that of all industries, the pharmaceutical industry is the closest to basic science (biology), adheres closest to the linear model of innovation, utilizes university inventions, purchases more licenses, and displays more university spin-off firms than other industries. The present analysis offers an explanation for this: the nature of the instrumental principles of pharmaceuticals is such that studying them simultaneously produces new knowledge of biological processes. Knowledge creation around such processes and principles is, thus, in the mutual interest of both the industry and the university, as it is likely to produce empirical and theoretical types of knowledge that can be easily published, as well as applicable knowledge that is useful for subsequent industrial product development.

Thus, based on the present analysis, in many industries, the nature of instrumental knowledge is proposed as a key factor affecting the prevalence of collaboration with universities. When research focuses on studying the natural phenomena produced in or by artefacts—as in heat engines—it tends to fall into the domain of "engineering science" rather than the more fundamental or university sciences, although the definition of engineering science is not clear-cut (Boon 2006). The present study points out that the less a technology works like a separate "machine" and the more it functions directly as a part of the useful natural phenomenon, the more likely it is that natural or medical science plays a meaningful role in the production of both instrumental and applicable knowledge. Examples of such technologies include drug compounds, antibodies, the recombinant DNA technique and new materials. Where de Solla Price (1984) saw that basic research should be defined as studying the world of nature and applied research as studying the world of the artificial (see Section 2.2), it can now be noted that the role of universities in applicable research is increasing as the distinction between the worlds of "nature" and "artificial" is becoming ever harder to draw. This is so especially with respect to genetic manipulation where the method is "artificial" but the outcome is just added information in the DNA of "natural" organisms. The findings of Thursby, J. and Thursby, M. (2011) are compatible with this view: they find that university researchers in bio- and nanotechnologies collaborate with the industry more than university researchers in other fields.

Whenever university research creates instrumental knowledge, it makes the initiation of novel innovation development possible. Naturally, the creation of instrumental knowledge is not limited to the realm of academia. It appears that essential for the emergence of novel inventions is the interplay between the questions of "what is needed" and "what is possible" (Stefik, M. and Stefik, B. 2004)—the making of new combinations between perceived needs and natural effects (Arthur 2007). The present study adds that this interplay that lies behind the invention process may have more than two dimensions or dispositions, and the process is likely to benefit from iteration and alteration between *empeiria, episteme, techne,* and *phronesis.*

5. Conclusion

The above analysis and discussion brings together research on knowledge, the university-industry relationship, the science-technology relationship, and knowledge transfer, and re-interprets these in the context of university-based knowledge creation. The proposed approach outlines four types of knowledge dispositions (*empeiria*, *episteme, phronesis, techne*), four types of propositional knowledge (empirical, theoretical, instrumental, applicable), as well as four types of research skill or procedural knowledge (methodological, analytical, inventive, and application skills) and how all of these relate to the production of inventions and innovations.

The framework in question contributes to research on the science-technology relationship and university-industry interface by deepening the understanding of the nature of the knowledge emerging from scientific research and its relation to industrial innovation. In particular, it shows that one important group of contributions that university research has been found to make to society—new technological inventions, patents, methods and instruments—can be conceptualized as a specific form of knowledge, namely instrumental knowledge. The framework also defines applicable knowledge from a new perspective, namely as knowledge that enables making the principles defined by instrumental knowledge operational. It is argued that this definition is less ambiguous than earlier distinctions between “basic” and “applied” research. Further, by showing that research produces many forms of propositional and procedural knowledge, the present approach extends beyond the tacit/codified distinction. In particular, the analysis shows how methodological research skills are a form of procedural knowledge, important for both scientific and technological progress but somewhat overlooked in the prior typologies of scientific knowledge. Finally, employing Aristotelian dispositions to knowing enables the presentation of scientific research as an iterative, fluid and creative process. From this perspective, the precise types of knowledge outputs need not be—in fact, cannot be—assumed beforehand; the various types of knowledge can be combined in many different ways, sometimes leading to or contributing to innovation, sometimes not.

All in all, the framework clarifies the qualitative aspects of what is comes to being when “knowledge” is created in the context of scientific research. It shows how the different types of knowledge have different functions with respect to technological development. The framework enables the posing of further questions of what is actually transferred in the knowledge transfer and how the division of knowledge labour in innovation takes place in specific organizational, industrial or spatial contexts. As globalization shakes the established industries, an approach capable of recognizing the different types of novel scientific knowledge and their relation to innovative technology development should be a welcome addition to the discussion on the knowledge-based economy.

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Manuscript 2: Höyssä, Maria. University-generated knowledge and innovation: The contribution of medical research to advances in health-care technologies

UNIVERSITY-GENERATED KNOWLEDGE AND INNOVATION: THE CONTRIBUTION OF MEDICAL RESEARCH TO ADVANCES IN HEALTH-CARE TECHNOLOGIES

Abstract

This paper studies how university research contributes to the technological innovation process. It analyses three cases of health-related research. The study is positioned in the discussion concerning the nature of economic knowledge, in particular the “learning economy” approach and the analytical and synthetic industrial “knowledge bases” approach. Both approaches argue that industrial innovation which is based on doing, using and interacting would benefit from being more well-connected to sources of codified knowledge creation in universities. The present analysis shows that the crux of innovation-relevant knowledge creation in universities is not codification but, rather, the development of different skill and knowledge types and the study of the basic principles of innovative technologies.

1. Introduction

Much remains unknown about the role of universities in knowledge-based regional economic development. The contribution of research universities to local development has been questioned (Feldman and Desrochers 2003) and policies for supporting spin-out activities have been met with scepticism (Miner et al. 2012; Mowery and Sampat 2005). It has been suggested that other roles of universities—such as building talent and networks—are probably more important for regional development than innovation activities (Wolfe 2005, 185-186). These discussions suffer from an incomplete understanding of what science-based knowledge is and what it does in the innovation process. This paper aims to address this gap.

Two prior approaches concern the nature of knowledge in the context of innovation-based economic development: the “learning economy” approach distinguishing know-what, know-how, know-why and know-who *types of knowledge* (Johnson et al 2002; Lundvall and Johnson 1994) and the approach outlining analytical and synthetic (as well as symbolic) *knowledge bases* of industrial activity (Asheim 2007; Asheim and Gertler 2005). These approaches have been created to characterize and analyze the role of knowledge in industrial innovation activity. In them, scientific knowledge is presented as a relevant, but not necessarily essential type of knowledge for innovation. The emphasis is, quite correctly, on the importance of non-scientific knowledge types for most industrial innovation. Scientific research is portrayed as involving mostly knowledge of know-why type and taking place mostly in universities or other public research institutes. Industrial product development, in turn, is regarded as involving know-how and a generally interactive approach to innovation. The problem is the superficial differentiation between academic and industrial knowledge creation processes. The dichotomous distinction does not help in explaining how industrial and university-generated scientific knowledge can be combined during the innovation process. Yet, both the knowledge types approach and the knowledge bases approach acknowledge an increasing need for a wider sphere of industrial innovation activity to build connections with scientific knowledge creation (Asheim 2012; Jensen et al 2007). To facilitate such connections, it is important to understand the nature of scientific knowledge and its role in innovation in more detail.

The present study takes a closer look at scientific knowledge in natural and medical sciences by analyzing the research trajectories of three individuals: the first led to the development of a novel scientific instrument prototype, the second involved the discovery of the health benefits of a certain sweetener, and the third gave rise to a new material in dental health care. Through these cases, this study analyzes *how knowledge created in university research contributes to the innovation process.* The analysis identifies what types of knowledge these researches created and what the role of these different knowledge types was in the emergence of the eventual innovations.

The analysis enables three significant observations regarding the role of scientific knowledge in innovation. First, it illuminates how some types of research knowledge and skill contribute to the innovation process by mediating between the analytical aspects of scientific research and the synthetic aspects of engineering practice. Second, the analysis suggests that learning by doing and using can be an important part of scientific research, even though it has previously been associated especially with industrial innovation. Third, the results indicate that the division of knowledge labour between university research and industrial development is not necessarily as static and given as the prior research indicates.

This paper is structured as follows: The following, second, section summarizes the current understanding of the nature of university-generated knowledge and its relation to innovation in the context of regional economic development. The third section introduces the analytical framework of the present study. The cases, data collection and methods are explained in the fourth section. The fifth section presents the results of the qualitative analysis, and the final section discusses the contribution of the analysis to prior research.

2. The nature of science-based knowledge?

Research of knowledge-based regional economic development rarely defines what knowledge is. The important property of knowledge, in this discourse, is to increase the competitiveness of firms through innovation. Knowledge is often implicitly presented as arising from the experience of practical problem-solving processes in firms, its creation driven by collaboration, competition or spillovers in clusters (cf. Malmberg and Power 2005). Knowledge is further distinguished/divided into tacit vs. codified forms (Polanyi 1962; Polanyi 1966). The actors in a learning region are assumed to produce, first and foremost, tacit and therefore strongly localized knowledge, which supports the specialization and subsequent competitive advantage of the firms in the cluster or region (Maskell and Malmberg 1999; Oinas 2002, 66; cf. MacKinnon et al, 2002). Knowledge created in universities is given less attention. When compared against the experience-based knowledge of firms, research-based knowledge is understood as more codified and more transferable. But multiple studies have shown that tacit knowledge is still required for the absorption of codified knowledge (Wolfe 2005).

The tacit/codified continuum only illuminates one dimension of knowledge: its explicitness. The related research focuses on the mechanisms, channels and policies of transfer for more or less codified knowledge. But the manner of transfer says nothing of the *function* of knowledge: what it adds to innovation and how. Howells (2001) seems to indicate such a shortcoming when proposing that research should find out the “what, when and how” of tacit knowledge transfer (ibid., 881).

Lundvall and Johnson (1994) characterize knowledge differently—as “know-what”, “know-why”, “know-how” and “know-who”. They propose that the combination of these knowledge types during the innovation process forms the entrepreneurial core of the “learning economy”. The taxonomy reveals many more dimensions to economic knowledge than its explicitness (Johnson et al. 2002). This framework has been proposed as suitable for characterizing differences in styles of innovation between nations (Lundvall 1998) and it has been used for explaining differences in competitiveness of firms (Jensen et al. 2007). The approach does not focus directly on the role of universities in the production of knowledge, but assumes scientific knowledge to have specific features. Jensen et al. (ibid.) introduce the so-called Science, Technology and Innovation (STI) and Doing, Using and Interaction (DUI) innovation modes. STI relies especially on the codified know-why of science. Know-who and tacit know-how are associated with DUI knowledge, which "regardless of the extent to which it is ultimately codified, is acquired for the most part on the job as employees face on-going changes that confront them with new problems" (ibid., 683-684). Jensen et al. (ibid.) argue that firms that manage to combine the STI and DUI modes of innovation are the most competitive.

Asheim and Gertler (2005; see also Asheim and Mariussen 2003) have sought another route beyond the tacit vs. explicit discussion. They distinguish between analytic and synthetic industrial knowledge bases to show that there are fundamental differences in economically relevant knowledge between different industries and regions. *Analysis* refers "to understanding and explanation of the features of the (natural) world" and *synthesis* concerns the "constructing something in order to attain functional goals" (Asheim 2012, 997). Science-based industries are argued to draw mainly on the analytic knowledge base: know-why knowledge, codification, formal models and interaction with universities. The engineering-based synthetic industries are portrayed as needing only applied research rather than input from universities: "Knowledge is created less in a deductive process or through abstraction, but more often in an inductive process of testing, experimentation, computer-based simulation or through practical work" (Asheim et al. 2011, 897). Asheim (2012) argues that firms relying on synthetic and symbolic knowledge bases need to develop relations with universities and other types of R&D institutions in accordance with the STI mode.

The knowledge bases approach is, nevertheless, unclear on the precise relation between knowledge and innovation. It presents analytic innovation as relying on scientific knowledge, laws and models. In synthetic industries, innovation is defined as taking place through the application or novel combinations of existing knowledge (Asheim et al. 2011, 897; see also Asheim 2007, 225; Asheim 2012, Table 1). If only processes of applying and combining knowledge, instead of creating it, take place during synthetic knowledge creation, are the above-mentioned inductive processes of testing, experimentation and simulation only methods for applying and combining existing knowledge? Why do they not create knowledge? Where does the "existing knowledge" come from that these methods apply or combine?

In sum, it has been argued that many fields of industry might benefit from integrating codified scientific knowledge into their innovation processes. But the assumption that science would produce exclusively know-why has been made somewhat lightly, and the nature and sources of existing, new, scientific, applied and combined knowledge in innovation are not clear. This creates a risk for misinterpreting the role of knowledge created in universities.

3. Science-based knowledge in this study

To understand how firms could better combine the DUI and STI modes of innovation, it is important to have precise concepts for characterizing knowledge. In order to allow for recognizing also other types of scientific knowledge than know-why, this study applies a conceptual framework of scientific knowledge creation (see Figure 1).

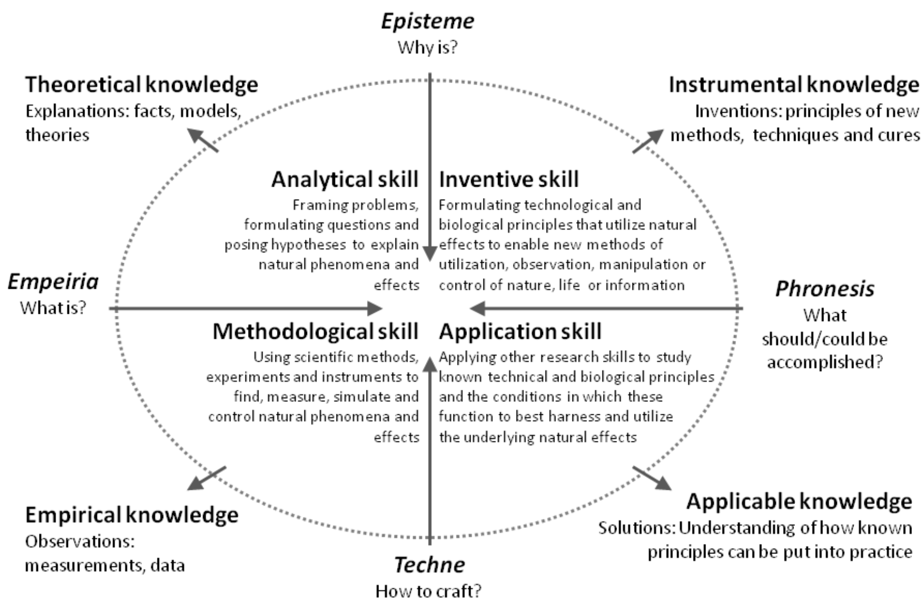

Figure 1 Types of research disposition, skill and knowledge (modified from the figure on p. 129).

In Figure 1, the oval shape represents research practice, consisting of the use of research *skills* (procedural knowledge), which are motivated by underlying research *dispositions* (inward arrows). Propositional *knowledge* is the output of research (outward arrows). There are four dispositions: the researcher may try to observe nature (*empeiria*), to uncover a-contextual regularities of nature (*episteme*), to create, craft, control or manipulate natural phenomena or technologies in specific contexts (*techne*)—or seek to determine what should or could be accomplished (*phronesis*). These dispositions are inspired by Aristotle's view on "virtues of thought" (Aristotle *Nicomachean*

Ethics: VI*; Parry, 2008*)—except for *empeiria*, which is not a virtue but one of the lesser dispositions (Aristotle *Posterior Analytics: II.19;* Butler 2003).

The different types of knowledge emerge as the two dispositions "surrounding" it (in Figure 1) coalesce: *Empirical knowledge* arises from trying to answer both what is and how to craft the proof for this. It consists of reported observations and data concerning natural phenomena and effects. *Theoretical knowledge* arises from trying to answer both what is and what regularities of nature explain it. It concerns explanations of natural phenomena and effects: novel facts, models, theories and laws. *Instrumental knowledge* arises from the efforts to answer both what should be accomplished and what regularities of nature would enable one to do that. It consists of principles of how a natural effect can be used to achieve a functional goal (Arthur 2007)—principles of novel technologies, methods, techniques and therapies. *Applicable knowledge* arises from efforts to define what should be accomplished and how to craft this into being. It informs how instrumental principles can be put to practice: why a principle works, the conditions and contexts in which it functions most reliably, or the range of problems to which it can be applied. To give examples, the models of radio wavelengths are *theoretical* knowledge. Observing different wavelengths produces *empirical* knowledge. The general principle of using the effect of wavelengths reflecting from metal to make a radar detector is *instrumental* knowledge. Determining what which wavelengths could best be used in a radar produces *applicable* knowledge.

Research skills are not independent; they require background knowledge of many kinds (not depicted in Figure 1). For example, *methodological* skill requires not only meticulousness in sampling but also the ability to determine what to sample, which in turn is connected to the *analytical* skill of posing research questions and to the *theoretical* knowledge base to be advanced. Yet each skill also portrays unique features. Thus, although *techne* is sometimes used to refer to all know-how or skill (Lundvall 1998, 421; Johnson et al. 2002, 250), it only means a disposition towards *craft*: "*Technê* is a disposition (*hexis*) that produces something by way of true reasoning; it is concerned with the bringing into existence (*peri genesin*) of things that could either exist or not" (Parry 2008, interpreting *Nicomachean Ethics, VI.4,* 1140a1-20). In scientific research, *techne* is concerned with the "bringing into existence" of *experiments, effects, observations, data and documentation of natural phenomena, as well as the techniques based on them, while episteme concerns the nature of underlining truths and regularities. Techne* can be understood as closely concerned with two research skills: first, the *methodological* hands-on creation of effects and observations and, second, the *application* skills to investigate how instrumental principles can be put to practice as technologies. Facing something unexpected during the act of crafting may give rise to questions of other dispositions: What happens here? (*empeiria*); Why does it happen in this way? (*episteme*); Should it be prevented or utilized for some purpose? (*phronesis*) and if so, then how? (*techne*). In this mediated way, *techne* may also be related to the *analytical* and *inventive* research skills. However, it would be misleading to say that all research skills involve *techne.*

In this study, the above-outlined typology is used as a framework for analyzing how the research process proceeded in the case examples. The analysis identifies dispositions, skills and knowledge types that were prominent in the different stages of the case research, as well as their potential role in innovation development.

4. The cases, data collection, and methods

The objects of this study were selected to as likely to display the different types of knowledge. Medical research was chosen as the empirical context, as it often involves opportunities for both creating new knowledge about natural phenomena and applying this knowledge for some practical purpose. The accessibility to and background understanding of the cases were enhanced by studying processes that took place in the same institutional context, the medical faculty of the University of Turku, Finland. Two of the three cases initially involved elements of more “basic” science, while the third was application-oriented to begin with. The cases produced the following inputs for the commercialization process:

(1) A prototype of the Sample Oxidizer, a research instrument that automatically prepares test animal tissue samples so that the concentration of radioactive marker compounds can be analyzed accurately. The instrument is used in studies of metabolism, especially in the context of drug development. The instrument was commercialized by US-based Packard Instruments in 1969. The related research and development continued at the University of Turku until 1977. (Höyssä and Hyysalo 2009)

(2) The caries-preventing effect of the xylitol compound. The effect is used in chewing gum, tablets and sweets that maintain or even improve oral health. The first xylitol product was commercialized in 1975 in Finland by the Huhtamäki Company. Xylitol-related research has continued to date at the University of Turku, but the intensive period of industrial collaboration was in the early 1970s.

(3) A fibreglass composite material, the applications of which include the repairing and strengthening of dentures and the non-invasive replacing of missing teeth. The first product from this line of research was commercialized

in 1997 by the university spin-off company StickTech. Intensive university research and industrial collaboration continues to date.

For methodological reasons, the focus of the analysis was put on the trajectories of individual researchers rather than those of larger research teams. The exploratory nature of this study calls for a research setting in which the different knowledge types can be discerned as simply as possible. This is most easily studied with respect to changes in the research interests of individual researchers. This may lead to an over-emphasis of key individuals in the creation of new knowledge, but it enables capturing the multi-faceted nature of the knowledge produced.

The data for the analysis has been drawn from two kinds of sources. First, three rounds of interviews were carried out with the inventors. The questions of the first round were open-ended, but in the later rounds, the questions were increasingly structured. The interviews lasted between one and a half and three hours. Two of the interviewees were over 70 years of age, although not fully retired from research. Their seniors could not be interviewed anymore. One of the interviewees was under 50 years of age. His closest senior was still available and was, thus, also interviewed, once. Additional background information was gathered from newspaper and Internet sources.

The second major source consisted of the researchers' publications, i.e. journal articles and patents. One of the researchers published only one journal article before becoming a full-time inventor (some 30 inventions by May 2012), one has published only scientific papers (315 by May 2012) and no patents, and one has been active in both fields (365 scientific papers, 16 inventions by May 2012). The full-time inventor's personal archive—plans, technical reports, instrument testing data, and some correspondence—substituted for the lack of scientific publications. The titles of scientific publications, (the) Finnish and U.S. patents, as well as patent applications of each study subject were put into chronological order and the apparent main research interests and changes in them were developed into a rough timeline. The timeline was supplemented with a more detailed analysis of the abstracts of journal papers from the first publication until five years after the first invention, as well as by the full text of the patents and patent applications that were created during that period. This analysis was further supported by taking into consideration review papers that described the evolution of these particular fields of science and technology (in particular, Rheinberger, 2001; Jagger et al, 1996; Dills, 1989).

The analysis has been divided into two phases: the analysis of the research that preceded the emergence of invention and the analysis of inventing and follow-up research. This narrative structure has been chosen to highlight the differences between knowledge which is, as yet, not focused on any certain instrumental principle and knowledge that concerns a specific technological solution. The narrative also includes short paragraphs (in *italics*) describing the "Eureka moment" of each inventor "as it happened". These are composed on the basis of the inventor descriptions during different interview rounds. The inventors have confirmed that these narratives adequately match their recollection of the incident.

5. Identification of knowledge types in academic research

5.1 Knowledge types before invention

The Sample Oxidizer. During his studies and research assistantships, the inventor-to-be of the Sample Oxidizer became convinced that achieving high quality *theoretical* knowledge required *empirical* knowledge of high precision.

> *I made several entries [into science] in which I was very passionately striving for scientific theory and accuracy] (...) In sociology, I was terribly interested of methodology. (...) then [I became a student] of experimental psychology, as an assistant to [professor] (...). [In disciplinary terms] we came very close to medicine (...) There was this conflict that one was not allowed to contribute to [research in] medicine (...) I constantly ran into the boundary between psychology and medicine. I did not tolerate it; I had to cross over [into medicine]. With test animals it was possible to measure emotions that had physiological consequences [...For this purpose] I re-invented the Skinner cage. (Compiled from two interviews of Inventor 1, 26.5.2006 and 25.8.2009)*

This desire to understand the physiological basis of emotions reveals a disposition towards *episteme*. It became combined with *empeiria*, observing the physiological processes of the test rats. The interviewee's attempts to study *theoretical* questions led him to be increasingly convinced that sufficient *methodological* skills were not available. Once he entered the medical faculty as a student, he soon became disappointed with the fact that the results of the hormone level measurements were compromised by the need to use such large concentrations of radioactive markers that test animals became ill. The existing method did not allow a reliable detection of such small doses of radioactive markers that the rat physiology would have remained natural. The student calculated that, in theory, greater accuracy should be achieved, but the precision was lost somewhere. He carefully observed the manual practices of the laboratory assistants and realized that the variation in the results was caused by their carelessness during sample preparation. Conventionally, the result variations had been attributed to biological variation in the test animals.

The student concluded that in order to improve the *theoretical* explanations, the method of sample preparation should somehow be automated to remove accuracy-compromising features. The purpose of the research project was to explain the role of noradrenalin in hypertension. The inventor-to-be developed a parallel *phronetic* mission that came to define the rest of his career: to improve biochemical methods.

Xylitol. The second case is the research trajectory of the co-discoverer of the dentally useful properties of xylitol sugar alcohol. In university, this young scientist studied biochemistry, supplemented with biology, chemistry and some physics. Basic chemistry laboratory skills formed the foundation for learning. In enzyme research, *methodological* skills were craft-intensive, as these instruments were not thoroughly commoditized at the time:

> *We (...) had to go to the city and fetch materials from the glass-blower's shop, chromatography columns, the design of which one could decide oneself (...) One went there on the basis of a plan, let's say in order to purify an enzyme protein. To do that, one needed smaller or larger glass columns. In other words, [the design] proceeded from the research need, the existence of these enzymes and their potential significance with respect to certain metabolic phenomena or diseases. (Inventor 2, 5.6.2012)*

The post-graduate research of the biochemist focused on a certain enzyme, aminopeptidase B. In 1965, one year into post-graduate research, he got a unique post as a chemist at the dentistry department. Globally, the leading dentistry departments were only beginning to introduce chemical and biochemical methods in addition to more traditional physiological and anatomical approaches. The biochemist was given an opportunity to lead the development of chemical laboratory methods in dentistry:

> *It dawned on me that there had been little research on the biochemistry of the mouth (...) I came into a situation where I could help a large number of assistants in their research with respect to biochemical methods. Even though I was young and inexperienced, I had a clear role there. (Inventor 2, 15.4.2010)*

Along with mentoring and doing his own research on the purification, characterization and functions of rat liver aminopeptidase B, the biochemist initiated biochemical research in the context of oral cavities. The boundary crossing from the *empeiria, episteme* and *techne* of biochemistry to the *empeiria* and *episteme* of dentistry took place literally overnight. On the laboratory leader's first day at the new post, he acquired saliva and plaque samples and began applying biochemical methods to study whether certain types of enzymes were present. But the *techne* of dentistry he never acquired or needed. After defending his PhD dissertation, the biochemist soon became an adjunct professor of biochemistry in dentistry, with expertise on clinical chemistry, protein chemistry and enzymology. As there was little prior knowledge of oral enzymes, he mostly produced knowledge of the *empirical* type. The underlining *theoretical* motivation was to advance the understanding of the role of enzymes in oral health and disease. In 1969, the biochemist started co-authoring articles with researchers with a background in dentistry. As the department was a stronghold of caries research, the articles concerned especially the role of enzymes in the formation of caries. The biochemist's research was not guided by any *phronetic* interest in practical problem solving. His aim was to exploit and refine his *methodological skills* to get to the front-end of the *empirical* and *theoretical* knowledge creation in a relatively unexplored sub-field in dentistry.

Fibre composite. The third case is the research path of an academic trained in dentistry a few decades later. This young man became interested in the lack of durability of dentures in his teens, when he was studying to be a dental technician. He had experimented with fibreglass reinforcement, which was an unconventional material in dentistry but familiar to him through his hobby, model aircraft construction. He was aware that, in other applications, plastic was routinely reinforced with fibreglass. So why not in dentistry, especially as the colour and hardiness of fibreglass were close to bone?

Later, the technician began his university studies to become a dentist. The technician's education had taught him the applied skill to craft dentures and denture reinforcements, but only a superficial understanding of the nature and properties of the commonly used materials, let alone novel ones. He entered university to develop his *theoretical* knowledge and *methodological skills* in order to truly understand the materials he worked with.

The dentistry education provided the dental technician with an orientation towards the actual treatment of patients and an even better *phronetic* understanding of the still unresolved user and end-user problems. He was able to do research alongside his studies, but he had to learn the necessary *theoretical* knowledge of materials science and polymer chemistry on his own. The knowledge of the different plastics used in dentures—let alone the more unconventional materials—were not part of the dentistry education. The University of Kuopio lacked the facilities for materials research, so he borrowed and customized devices for *empirical* research and began upgrading his dental technician's skills with the *methodological* skills of a materials researcher.

The dental technician's first publications concerned the prevalence of denture breakage, the limitations of commonly used metal reinforcements, and the performance of fibre reinforcements that he himself developed, as well as that of dentures repaired with resins. His motivation for studying competing solutions was to better understand the reference points of fibreglass solutions. Most of the research consisted of *empirical* fatigue tests, or strength tests of the adhesion between joined materials. This produced *applicable* knowledge relating to various existing *instrumental* principles of denture reinforcement. The dental technician, however, used the knowledge and skills thus gained to develop *applicable* knowledge around his own, emerging, fibreglass principle. He actually went to a local patent office for advice, but was only told that fibreglass cannot be re-invented.

The technician graduated in dentistry in 1994, simultaneously receiving both a Master's and a Doctoral degree. After his Doctoral defence, the opponent from the University of Turku—who had developed the so-called bioactive glass concept for orthopaedic applications—decided to recruit the promising researcher to his department at the first opportunity.

Table 1 summarizes the main examples of disposition, skill and knowledge that were developed in this first period of each case research trajectory.

Table 1 Examples of main dispositions, skills and knowledge developed in the first period of case research processes.

	SAMPLE OXIDIZER	XYLITOL	FIBRE COMPOSITE
DISPOSITIONS			
Empeiria	What are the accuracy-limiting steps of the test method?	What are the characteristics of aminopeptidase B? What enzymes are present in the oral cavity?	What are the properties of various denture materials?
Episteme	What is the physiological basis of emotions? What is the role of noradrenaline in hypertension?	What are the functions of aminopeptidase B? What is the role of enzymes in oral health and illness?	Why are existing denture materials inadequate?
Phronesis	The measuring variance of radioactive sample tests should be decreased	(No attempts to define practical goals)	Dentures should be stronger
Techne	How could radioactive sample preparation be automated?	How can good data for enzyme research be produced?	How can fibreglass reinforcements with desired properties be crafted?
SKILLS			
Methodological	Statistical methods	Biochemical methods	Fatigue and strength tests of denture materials and reinforcements
Analytical	(No attempts to provide new explanations for natural phenomena)	Formulating research questions to explore oral biology from a new angle	(No attempts to provide new explanations for natural phenomena)
Inventive	Using a statistical understanding of the issue to identify the shortcomings of the prevailing method	(No attempts at solving practical problems by utilizing natural effects)	Defining the desired properties of the potential new material
Application	Revealing the sources of variations in the manual sample preparation practices	(No research on a certain instrumental principle)	Designing studies for understanding the limitations of various denture reinforcement principles
KNOWLEDGE			
Empirical	Measuring noradrenaline levels in rat tissue	Characterizing the properties of aminopeptidase B; Measuring the presence of certain enzymes in plaque and saliva	(All *empirical* results were applicable rather than “basic”)
Theoretical	Unpublished study on noradrenaline metabolism	Contributions towards understanding the function of aminopeptidase B and the role of enzymes in oral health and disease	(No theoretical knowledge creation)
Instrumental	(No inventions)	(No inventions)	(Incomplete definition of the fibreglass reinforcement principle of dentures)
Applicable	(No research on a certain instrumental principle)	(No research on a certain instrumental principle)	Studies characterizing various materials and the scope of their applicability

5.2. Knowledge types after invention

This section highlights the emergence of *instrumental* and *applicable* knowledge as different from *theoretical* and *empirical* knowledge. It also shows that while each research process focused on gaining a thorough understanding of the natural phenomena related to the instrumental principle of the invention, they produced a different mix of knowledge types.

The Sample Oxidizer. The student / research assistant had not yet formed an independent research career before he made his first invention. This happened while doing measurements for a research project studying the causes of hypertension:

The assistant had prepared the test to analyze the concentration of hydrogen and carbon, the best labels at the time. He burned the sample. It would take some half an hour for the radioactive vapours to diffuse in the alcohol at the bottom of the glass container. The assistant could not believe the slowness of the process. What a waste of time! Could one perhaps increase the speed by manipulating the temperature and distance…? Yes, but metal rather than glass should be used, as metal has a thermal connectivity, which is orders of magnitude better. Using the formula of the diffusion speed, the assistant calculated that if—instead of using a glass surface at a distance of 30 cm—the vapours were forced directly into a cold metal tube with a radius of half a millimetre, the radioactive liquid would condense in 0,005 seconds rather than in half an hour. And one could leave out the alcohol, which would further significantly improve the accuracy of the method. The assistant borrowed the money for the materials to make a prototype. When the representative of Packard Instruments was visiting the Department of Physiology on other business, the assistant showed him the primitive but functioning device. It did not take many weeks before the inventor was invited to the United States, from where he returned with an agreement to commercialize the invention, the Sample Oxidizer.

It is impossible to tell why the other users of the existing instrument did not have the same revelation, but it seems plausible that a mere *epistemic* or *empiric* drive for new knowledge would not have sufficed; one could always choose problems for which the performance of the instrument was sufficient. The disposition towards *techne* alone would not have had this result either. *Phronesis*—the disposition towards solving a practical problem, like in this case the variations in test results—was a precondition for the invention. It drove the inventor to question the conventionally used materials and the operating principles of prior instruments. But interplay between the different dispositions was also needed for a thorough understanding of the nature of the practical problems at hand.

Packard Instruments provided funding for a small team to further develop the prototype in the university's facilities. The *theoretical* knowledge needed was that of physics and chemistry rather than physiology. The skills required for the actual prototyping were those of a mechanical engineer. The inventor recruited a physicist-chemist and a mechanic, and Packard supplied additional chemistry expertise. The *applicable* knowledge creation focused on optimizing the functioning of the instrumental principles. Also further *instrumental* knowledge was acquired. Both types of knowledge concerned the controlling of the movement and temperature of liquids and gas in small spaces. There was no attempt to connect this knowledge to a more generic *empirical* or *theoretical* disciplinary framework; it remained entirely within the context of developing a particular technology. Monthly reports were sent to the sponsor, but Packard Instruments never needed to learn the *application* skills from the team or understand the underlying physics. The company simply replicated the prototype designs: the core parts of the product have remained essentially unchanged to date.

As the Sample Oxidizer came on the radioactive sample preparation market, competition soon evaporated. So did Packard's need for the development team. The team members left the university. The team's funding arrangement had only allowed it to publish its results for industrial marketing purposes, so no academic articles had been published. Yet the equipment enabled altogether new physiological research questions to be posed. Leading international pharmaceutical companies quickly adopted the Sample Oxidizer, and it was used also in many university departments. Follow-up research to the oxidizer principles continued elsewhere, but without connections to any academic context.

Xylitol. The second case came to contribute to innovation in 1969, when the research collaboration between the biochemist and his colleagues in dentistry had only recently been established and those involved were open to new research opportunities:

Three men from Finnish Sugar Co. were visiting the Department of Dentistry. The professor of dentistry, as well as the docent of biochemistry of dentistry met the businessmen in the negotiation room. The academics got to hear that Finnish Sugar had developed a mass production method for xylitol and was looking for uses beyond sweetener for diabetics. Could the sugar alcohol xylitol replace ordinary sugars in some other context? Academics began considering the molecular structure of the xylitol compound. It was known to have five carbon atoms, whereas fructose, glucose and sorbitol had six. The professor, who had specialized in caries, realized that caries bacteria should not be able to consume the five-atom structure. The researchers wanted to study how xylitol would affect caries when digested... The results of the pilot study were *astonishing: the use of xylitol-sweetened tea decreased the prevalence of bacterial plaque in teeth by 50 %. A few years of ample industrial funding followed. As xylitol turned out to meet and even exceed the specifications of a non-cariogenic sweetener, xylitol products started to flow onto the Finnish consumer market in the mid-1970s.*

In the discovery and invention of the dentally beneficial properties of xylitol, the professor of dentistry and the docent of biochemistry of denistry combined their *theoretical* and *empirical* knowledge from a practical, *phronetic* angle, prompted by the question of the representatives of the sugar company. Both men were quite aware of the big practical problem of dentistry in Finland: Finnish people had teeth that were still badly infested with caries. Something new besides fluoride was needed. They also knew that another sugar alcohol, sorbitol, had had already been tested as a potential non-harmful sweetener in the United States, Britain and Denmark. Even though the two researchers had not been involved in industrial collaboration before, it became natural to frame research questions in terms of practical relevance once such a possibility so obviously had opened up. But *phronesis* was not all there was to it:

> *I must say that for the main part, they [the xylitol studies] represented applied research. The aim was to apply this idea to reduce caries. However, my education tended towards basic research and I saw what an opportunity there was to simultaneously create basic research data in this experiment, which was challenging to create in itself. There were some 140 experimental subjects at a time, altogether over 300. (...) We also studied such chemical substances that did not appear to have any connection to the emerging use of xylitol (...). Without this basic approach, we would not know now that the use of xylitol increases the protein as well as nitrogen metabolism. This enables us to explain the mechanism through which xylitol functions. (...) If we had only given the experimental subjects xylitol and then measured the activity of caries at frequent intervals, the result would have been what the Finnish Sugar Company had desired: xylitol does not induce caries, and it may even repair some damage of dental enamel. Now, however, we did all kinds of tests and experiments, even collected exudate samples from gum pockets with filter paper and analyzed them with various tests. This is how we saw that the infection processes in the mouth and gums were reduced during the xylitol diet. (Inventor 2, 15.4.2010)*

The interviewee is using the concepts of basic and applied research to differentiate between academic and commercial interests. Looking at the quote through the analytical lenses of the present paper, we notice that he makes a subtle point about *applicable* knowledge: to really understand how the invented principle works, one cannot restrict research to solving the pre-defined problems set by external parties. Researchers must have the freedom to explore related *empirical* and *theoretical* knowledge, which may or may not result in illuminating the *instrumental* principle.

The industrial xylitol funders recognized this. The research team was supposed to study xylitol and other sugar alcohols, but they were free to choose the specific research questions. The funders never ordered a single study but were only informed of the results. The xylitol team studied, for example, the chemical properties of saliva and the metabolism of bacteria and yeast in the mouth during the xylitol diet. Thus, they found out, for example, that xylitol loosens plaque and makes it easier to brush off. The researchers also explored other avenues. For example, when they discovered that xylitol affected the functioning of the salivary gland, they immediately proceeded to study whether it had an effect on the mammary gland as well. Unlike in the other two cases of the present paper, there was little need to customize the existing methods for the study of the instrumental principle. No further *application* skills thus needed to be developed; the group simply exploited their *methodological skills* to create *applicable*, *empirical* and *theoretical* knowledge. The results provided scientific credibility to the marketing campaigns. For example, academic laboratory slang was used to advertise how xylitol chewing gum "stops the acid attack" against the teeth, and the claim was further supported with graphics from the xylitol research.

The fibre composite. Immediately before making the fibre composite invention, the inventor worked as a post-doctoral researcher in a Norwegian laboratory with some of the world's leading specialists in the base material of dentures, acrylic. As he sees it:

> *Without this period, even if [my invention] had become a product, I wouldn't have had the proper expertise to talk about it; the knowledge gaps would have been too wide. Knowledge-wise, you have to be ahead of everyone else. This knowledge related to the polymerization of plastic structures, how one can inhibit it and how it advances. It was basic knowledge, accumulated only in the minds of few people, globally. (...)My head was full of questions, and once a week I got to sit down with a polymer chemist and ask "what if" and "how to", and received immediate an-*

> *swers, references and all. Those references were absolutely crucial; they still feature in my publications. (Inventor 3, 4.6.2012)*

Studying the *theoretical* knowledge and related *techne* taught the inventor to understand the relevant materials. His research and dentistry practice had shown that the ideal reinforcements of dentures needed to be tough, light, slightly flexible, and non-toxic. The material should feature adhesion to the base material of the denture and not create any roughness on the surface of the denture. His fibreglass solutions were almost, but not quite good enough. The fibres were difficult to wet thoroughly with the plasticizing agent. The remaining void spaces caused structural weaknesses in the reinforcement. One day this remaining problem was finally solved:

The day in the dentistry research laboratory was over and it was time to tidy up. A vessel that had contained plastic material needed to be cleaned. The instructions forbade the use of water, but the researcher decided to take a little shortcut and put the vessel under the tap. The plastic began emulsifying and foaming. The researcher left the bubbling vessel waiting while he tidied up the rest of the laboratory. Then he returned to the foam, which turned out to have dried into a peculiar porous substance. Under the microscope, it seemed to suggest that a perfect reinforcement material for dentures would be a matrix with layers of fibres coated with polymer powder and this kind of dried foam which he had just discovered. The porosity of the matrix would allow a plasticizer to thoroughly and evenly infiltrate the fibres. This combination might even work as a repair material of teeth. The researcher hurried to patent the solution.

The invention took place in 1995. Around that time, the inventor was recruited to the University of Turku, where he was provided with additional funding to improve the facilities of the materials research laboratory. The researcher had been working on the problem of fracturing dentures for over ten years: as a technician making and repairing dentures, as a dentist treating patients and fitting dentures to them, and as a researcher trying to understand and solve the problems that the “technician” and “dentist” were facing. Having had this extended look at the problem from the perspectives of multiple dispositions, he could see an opportunity in a situation that to others would just have been a minor mishap. The porosity of plastic was a new observation for him personally, but it did not lack *theoretical* explanation. The novelty lay in discovering the usefulness of the pores for a specific purpose. The novel idea represented *instrumental* knowledge. It spelled out the principles with which the natural effect of polymerization could be harnessed to make a material with desired properties. A spin-off company was formed to commercialize it.

This inventor stayed in the academia to do further research on fibre composites. He began studying the properties and interactions of related materials and their environment also at the molecular level, to make sure that the innovative products of the company matched the promises, also in the long run. These studies resulted in some knowledge of *theoretical* nature, too, when the microstructure of adhesive bonds was revealed. Also new *instrumental* knowledge was published as patent applications and patents. Most of the knowledge produced was, however, *applicable*. It defined the properties and the scope of applicability of the solutions. It was produced by using bending tests and fatigue tests on denture specimens with different reinforcements and different storage times, for example. Respective publications were published in academic journals—at a very frequent rate:

> *I've been lucky in that there was no-one else studying those fibres, there was no practical competitor. It was problematic also, not to have any reference elsewhere. But the publications could not be easily rejected, as long as certain basic criteria were fulfilled. If you think of fluoride or xylitol, the research front is so crowded that one cannot really enter it. But what I have done has only recently been copied elsewhere in the world. When I pondered whether to join the [spin-off] company or not, I already saw that [my] papers were easily accepted. I thought that research is probably a more secure way to advance the issue (...). And it has turned out to be a good solution: we have a veritable publication machine, every two weeks a paper is submitted. No one can catch us in fibre applications. (...) It is kind of a mill that started churning and there was no resistance. (Inventor 3, 6.5.2010)*

Table 2 summarizes the main examples of disposition, skill and knowledge that were developed in the latter period of each case research trajectory.

Table 2 Examples of main dispositions, skills and knowledge types developed in the post-invention part of the case research processes.

	SAMPLE OXIDIZER	XYLITOL	FIBRE COMPOSITE
DISPOSITIONS			
Empeiria	What happens to the sensitivity of the instrument when its physical dimensions and materials are changed?	What are the effects of xylitol use?	What are the properties and interactions of plastic and fibre composites?
Episteme	What regularities of nature determine the flow of liquids and vapours in small spaces?	What regularities of nature explain the effects of xylitol use?	What regularities of nature explain adhesion between two polymers?
Phronesis	Which specifications should the automated instrument fulfil?	What health effects could be accomplished with xylitol?	Which specifications should the fibre composite materials fulfil?
Techne	Which materials and production processes would best enable the fulfilling of these specifications?	How should the health benefits of xylitol be created and studied?	How should the fibre composite materials best be manufactured and used?
SKILLS			
Methodological	Liquid scintillation counting chemistry, measurements & testing	Biochemical methods	Fatigue tests, bending tests, scanning electron microscope etc.
Analytical	Natural phenomena were not explained; instrument performance was *explained by* natural phenomena	Formulating research questions to explore oral biology from a new angle	Only some questions to explain natural phenomena; fibre composite performance was *explained by* natural phenomena
Inventive	Defining the principles of the automated sample preparation instrument	Identifying biological processes which xylitol affected usefully	Defining the desired properties of potential new materials and the processes to achieve them
Application	Designing studies to illuminate how liquid films are formed and replaced within the instrument	(No customization of research approaches was needed to study how xylitol could best be used)	Designing studies to reveal different aspects of the properties of the fibre composites
KNOWLEDGE			
Empirical	(No empirical knowledge--the aim was to enable users to create empirical knowledge with the instrument)	Measurements of plaque properties and oral enzymatic activity during a xylitol diet	(Some studies of the structure of adhesive bonds between two composite materials)
Theoretical	(Novel scientific explanations were not pursued)	Explaining why xylitol affects the biochemistry of the oral cavity	(Explaining what happens at the interface of two bonding composite materials)
Instrumental	Principles enabling the automation of radioactive sample preparation	Principles outlining how xylitol can be used to improve oral health	Principles of manufacturing and using novel fibre composite materials
Applicable	Findings concerning the performance of the prototype and supporting or constraining effects	Findings concerning how the xylitol principle can be most effectively used to improve dental health	Findings concerning the scope of applicability of fibre composite materials for different uses in dentistry

6. Concluding discussion on science-based knowledge and innovation

The purpose of this analysis was to inform how knowledge created in university research contributes to the innovation process. The study was framed against the knowledge type approach initiated by Lundvall and Johnson (1994) and the knowledge bases approach initiated by Asheim and Gertler (2005). Both approaches seek to understand the role of knowledge in industrial innovation. However, they define the role of science in innovation as mostly producing know-why knowledge. This may lead to an over-emphasis on the role of theoretical explanation in university research. The present analysis shows university research as potentially producing four types of (propositional) knowledge and cultivating four types of skill (procedural knowledge) in the process, driven by four dispositions, each representing a different type of approach towards natural phenomena.

Prior research does not address *how* scientific knowledge contributes to innovation. In an application of the knowledge bases approach, Moodysson et al. (2008) observed that academic research may switch from the analytical to the synthetic mode. But the switching is not really explained, as their dichotomous conceptualization of know-why (analytic science) vs. know-how (synthetic engineering) cannot account for any intermediary forms of knowledge. According to the present analysis, *instrumental* and *applicable* knowledge are these intermediary forms. *Instrumental* knowledge concerns new ways to solve practical problems by using specific natural effects. The principles of the Sample Oxidizer, xylitol and the novel fibre composite are examples of such knowledge. *Applicable* knowledge enables the operationalization of *instrumental* knowledge. It focuses on harnessing natural phenomena rather than explaining or describing them. Most knowledge created in the post-invention phase of the fibre composite and the Sample Oxidizer research was *applicable*, while the xylitol research produced *theoretical* and *empirical* knowledge, as well.

These concepts can be used to express more precisely what is knowledge is new and what has been known before in innovation. When Asheim et al. (2011, see Section 2) refer to “new scientific knowledge” as the basis of radical innovations in industries with an analytical knowledge base, we can understand it as new *instrumental* knowledge arising from scientific research. Synthetic or incremental innovation has been expressed as “applications or novel combinations of existing knowledge” (Asheim et al. 2011; Asheim and Gertler 2005; see Section 2). This means that *new applicable* knowledge is needed to apply or combine *well-established instrumental* knowledge.

Research on knowledge-based economic development recognizes something resembling *applicable* knowledge—but associates it misleadingly with its assumed context of creation: Jensen et al. (2007, 683), for example, refer to "science-like" knowledge that "pertains to particular artifacts and techniques" and is "created in industrial R&D laboratories". Asheim (2012) refers to "applied research undertaken at (technical) universities, which clearly must be part of the STI mode, but mainly operates on the basis of synthetic (engineering) knowledge". The present study claims that *applicable* knowledge should be recognized according to its underlining instrumental principle rather than by its assumed organizational context. In the case of xylitol, the *empirical*, *theoretical* and *applicable* knowledge were created at the university while the product and process innovations were developed in the industrial lab. In the case of the fibre composite, the *applicable* knowledge and the production process of the novel material were created in the university context, while the spin-off company refined the material into a commercial product. In the case of the Oxidizer, the university context was virtually transformed into an industrial R&D laboratory, as the work focused solely on prototyping and no academic publishing of the resulting knowledge was allowed. These examples show that the type of knowledge created at a university cannot be assumed *a priori*; research sites and projects may differ in this regard.

Research on knowledge-based economic development emphasizes the role of tacit know-how in industrial innovation and that of codified know-why in scientific research. It ignores the role of skills in scientific research. This is implied in the study of Jensen et al. (2007), which claims that "[f]irms that connect more systematically to sources of codified and scientific knowledge are able to find new solutions and develop new products that make them more competitive" (ibid., 690). Based on the present analysis, firms might benefit more from connecting to research skills rather than to codified knowledge. For example, the cases displayed *methodological* skills that were new to each disciplinary context. They were developed through "doing and using", often in close connection with the practical problems to be solved. This formed a fertile ground for scientific and technological advances alike. The analysis suggests that companies perhaps do not need to combine the DUI mode of industry with the STI mode of science, as Jensen et al. (ibid.) propose, but rather with a "DUI mode of science". Even the choice of Jensen et al. (ibid.) for indicators of the STI mode (positive expenditure on R&D, employees with academic degrees in natural science or engineering, and interaction with university or scientific institute researchers) seems to relate to the development of and access to research skills rather than to codified knowledge.

The final nuance added by this study concerns research dispositions. Prior research has discussed science-based knowledge by the type of its "content" or according to its degree of explicitness. The present study shows that the perspectives from which scientists approach natural phenomena are also relevant.

Phronesis—the disposition towards practical problem solving—was crucial for keeping research in fruitful contact with the process of innovation development. Without the other research dispositions, however, any attempts to fulfil a *phronetic* purpose would become mere trial-and-error. Even though only the xylitol research produced *empirical* and *theoretical* knowledge to any significant degree, also the other cases featured inquiries of *epistemic* and *empirical* nature. The interplay between the multiple dispositions amounted to a rethinking of the relationship between research problems, practical needs and methods, in a way that produced new creative solutions.

The present study has sought to illuminate the early phase of one of the foundations of knowledge-based economic development—the emergence of the science-based innovation process. While such processes are only small undercurrents in the broader stream of socio-economic development, they are at the focus of so many hopes, beliefs and policies that they deserve to be understood as thoroughly as possible.

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