Knowledge dynamics of interdisciplinary research in science-based technologies

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Abstract: Collaboration between different academic disciplines has long been viewed as one of the drivers of technological change. This is especially the case in science-based technologies and (Reger & Schmoch 1996; Grupp, 1992, Meyer-Khramer 1997), suggest that the development of science-based technologies is dependent on and perhaps even driven by, interdisciplinary collaboration. In spite of many attempts, there is still limited understanding of the knowledge dynamics of interdisciplinary research, as suggested, among others, by Bruce *et.al* (2004) in their evaluation of the EU-framework programmes. This paper takes a collaborative learning perspective and reviews the more recent discourse on interdisciplinarity in light of this. It then draws upon the findings of two empirical studies of interdisciplinary research within nanoscience and nanotechnogies, arguing that although interdisciplinary collaboration does indeed contribute to technological change, it does not automatically result in interdisciplinary knowledge. The paper concludes with a more nuanced conceptualisation of the knowledge dynamics in interdisciplinary research than suggested in earlier literature. The potential implications for research policy are discussed.

1. Introduction

During the last two decades European science and technology policy has included initiatives designed to encourage collaboration between different disciplines suggesting that policy makers think that this kind of research has the potential to provide new solutions to global problems, speed up research and improve the ability to find creative solutions.

During their studies on research in science-based technologies Reger and Schmoch (1996) found that researchers educated within different scientific disciplines worked together without problems, however communication between biologists and computer scientists and between doctors and electronic engineers was difficult. They gave these examples the label “big interdisciplinarity”, using the term to describe situations where participating disciplines are considered to be far apart from each other in ways of working and use of theories and methods. In their studies Reger and Schmoch found few institutes attempting “big

interdisciplinarity", however the institutes who did achieve this were noticeable in their success and their contributions to progress in the field (ibid:370). This paper takes this as its point of departure and attempts to look more closely at big interdisciplinarity in the development of science-based technologies and review the possible implications for policy.

This paper is divided into four sections, the first section consists of a short overview of the discourse on the theme of interdisciplinary research. The second section reviews studies on research practice to see how the theme of interdisciplinary collaboration is addressed. This is followed by an analysis of the findings of two recent case studies on interdisciplinary practice in the development of science-based technologies and in the final section the implications for research policy are discussed.

2. Why the interest in interdisciplinary research?

Some have viewed interdisciplinary collaboration in science as a natural phase in the development of new disciplines (Lemaine *et al*. 1976; Lenoir 1993, Klein 1996), i.e. suggesting that scientists reach the limits of their own field, branch out beyond it and work with others for a period of time until a new discipline or sub-discipline becomes established. Interdisciplinary collaboration is therefore seen as something temporary, not anything that scientists should strive towards. This conceptualisation views interdisciplinary collaboration as something which happens frequently and not as anything new, rather as something which has existed as long as disciplines have existed. This concept of interdisciplinary research is based largely on historical case studies tracing the emergence of new fields.

Another conceptualisation of interdisciplinarity is related to the structure of knowledge. This concept is often used in policy discourse related to knowledge production and suggests integrating fields of knowledge, in order to produce new knowledge. These fields of knowledge may be separated by the boundaries between university disciplines, between university and industry or between academia and the public. (Klein 1996, Becher and Trowler 2001, Gibbons *et al*. 1994). The various studies I have grouped together here all see greater collaboration between the different disciplines in terms of a new trend in knowledge production, not just as a temporary situation. I will outline some of the more important works relating to this idea of a new trend in knowledge production.

During the 1970s the OECD commissioned a group of experts to develop the concept of interdisciplinary research and education. The way they did this was to define what interdisciplinary meant to them:

> Interdisciplinary – An adjective describing the interaction among two or more different disciplines. This interaction may range from simple communication of ideas to the mutual integration of organising concepts, methodology, procedures, epistemology, terminology, data and organisation of research and education in a fairly large field. An interdisciplinary group consists of persons trained in different fields of knowledge (disciplines) with different concepts, methods and data and terms organised into a common effort on a common problem with continuous intercommunication among the participants from the different disciplines (OECD, 1972: 25 – 26).

Many of the contributors to this work (OECD, 1972), appear to have been guided by the idea that a greater unity of science would produce alternative ways of generating new solutions within science and technology. The work of Jantsch (1972) produced, as part of this initiative has been quite influential in defining the different types of contact disciplines might have. He developed a terminology describing a range of different modes of contact between disciplines, where each mode was designed to achieve different aims. He defines the type of contact in terms of steps from weak to strong (Jantsch 1972:15), with weak being "pluridisciplinary" or non-coordinated contact between scientists in order to solve problems or achieve a particular aim such as developing a new product. The steps continue via crossdisciplinarity and interdisciplinarity to (strong) transdisciplinarity, aimed at transforming the organisation of science in separate disciplines. Although Jantsch's terminology has not been adopted in a consistent way, his ideas of weak and strong interdisciplinarity (or transdisciplinarity, as he calls it), have been widely used. Lattuca (2002) is also influenced by the work of the OECD, however she interprets it as a kind of continuum with the informal communication of ideas at one end and more formalised collaboration at the other end. (ibid:712).

Shortly after the OECD conferences and publications on this theme another important work on the subject was produced The *New Production of Knowledge* (Gibbons *et al*. 1994). In this

work the authors see what they regard as a new trend in the development of science and technology. They place interdisciplinary research within a wider framework of the democratisation of science. They see the process of knowledge production as a process involving multiple participants, iterative patterns and lots of feedback at all stages throughout the process. They call this “mode 2 learning” and present it as a new way of working whereby research is carried out closer to the application or to the user of the technology. Research is no longer viewed as being embedded within a traditional discipline. They suggest that the close links a researcher might have had to the academic discipline within which he or she was educated are becoming weaker and that researchers and developers must learn to work with others, who may have a very different education and work experience. Mode 2 learning, which they also refer to as transdisciplinarity or “mode 2 knowledge production”, is distinct from “mode 1”. Mode 1 is viewed as a sequence of isolated phases of knowledge generation occurring in academic environments then passed on to the outside world in order to be further developed in new phases. In mode 1, academic researchers are seen as trying to increase their understanding from within the framework of their own discipline. Their results are then typically picked up and developed into technological applications by industrial actors. Mode 2 on the other hand is multidisciplinary, indeed it includes all stakeholders, users and the public. One of the important aspects of this concept is that it includes knowledge production outside academic environments. The authors suggest that any attempts to understand the development of technological knowledge should not be limited to academic or to industrial environments, but should take account of both. The ideas in this book have been criticised particularly for their lack of empirical data. In spite of all the criticism the concept of Mode 2 knowledge production has been very influential in shaping recent research policy in Europe.

In the aftermath of the *The New Production of Knowledge* (Gibbons *et al*. 1994) the suggestion that interdisciplinarity is a new trend in knowledge production was questioned by, among others, Weingart (2000). He takes another look at the reasons for why interdisciplinarity is so desirable and concludes that this is not a new trend at all, but is a perfectly normal and necessary part of the development of science. Weingart has studied the discourse on interdisciplinarity and he points out that many studies praise the creativity of interdisciplinary work, or highlight the necessity of input from multiple sources to solve

modern problems. In spite of all the positive reasons for removing traditional disciplinary organisation, it is still very much present and the training of researchers in science and technology is still predominantly within the structure of the traditional university disciplines. Weingart does not really see this as a puzzle, but suggests that interdisciplinary research has perhaps always been there and that it is not disciplinarity versus interdisciplinarity that is the important issue here, but rather that interdisciplinarity be acknowledged as an important part of innovation or new thinking in science and technology.

Although these views of interdisciplinarity are very different, they all see collaboration between the disciplines as being a source of new solutions or where the involvement of multiple disciplines is seen as something, which will have a positive effect on the outcome. This discourse says nothing to discourage big interdisciplinarity, indeed they include collaboration between the sciences, social sciences and humanities. Without subscribing to the idea that interdisciplinarity or indeed mode 2 is an entirely new trend, one can conclude that the study of collaboration between researchers with different disciplinary backgrounds provides a relevant starting point for the current study. In the rest of this paper the term “interdisciplinary” is used as an adjective describing research collaboration involving participants who are educated and have worked within different disciplines or as an adverb describing a type of activity involving participants with different disciplinary backgrounds.

According to the Jantsch framework, studies of research practice at the level of a research project or institute would be classified as weak interdisciplinarity if there is no deliberate aim to promote interdisciplinary collaboration for its own sake, nor any deliberate attempt to move disciplinary boundaries. On Lattuca’s continuum, this paper work would probably would fall under the category of formal collaboration, although there are examples of ad-hoc contact occurring before it becomes formalised.

None of the works reviewed so far attempt to describe how the different disciplines learn from one another, however there are many micro studies of research practice. Although these studies do not specifically investigate interdisciplinarity, they do address it in different ways. Some of these studies will now be discussed.

3. Interdisciplinary research in practice

Most of these studies reviewed here look at an array of factors which might influence the production of creative results in research teams or communities. Pelz and Andrews (1966) analysed results of 1300 questionnaires sent to scientists and engineers in industry and academia. Most of their findings were related to organisational factors, but they also found that the successful teams had more contact with people outside their own field. Stankiewicz (1980) in his studies of Swedish research institutes found a similar link between working in multidisciplinary teams and productivity. In his studies of university/industry links he also found a contradiction between the organisation of research into projects, which were often multidisciplinary, and the criteria for advancement in a research career, which were based on disciplinary specialisation. Carayol and Thi studied researchers at a French university to find out if working in a multidisciplinary environment produced more collaboration. They found that it did, but noticed in line with e.g. Stankiewicz (1980) that there was a "tension between problem-driven interdisciplinary work and the discipline-based academic career structure" (Carayol and Thi 2005:77). Hollingsworth and Hollingsworth (2000; 2004) carried out 200 interviews and 24 case studies in bio-medical research institutes in the US. They identified a correlation between disciplinary diversity and new discoveries. They describe how scientists with broad experience in different disciplines were recruited at the Rockefeller Institute. They describe the open and unstructured organisation of offices, laboratories and tasks and in particular the rich interactions, including the less formal ones such as conversing over lunch, between scientists of different disciplines. They suggest that commonalities, such as all being scientists, made it easier to communicate than in colleges such as those in Oxford and Cambridge where arts and sciences are expected to mix. Gulbrandsen (2004) investigated creativity in research laboratories and his results emphasise the importance of openness to external stimuli and input from other specialities in order to increase creativity: "when researchers to a lesser extent are challenged or informed by perspectives from other specialities, this may reduce the conditions for creativity" (ibid:54). Heinze *et al*. (2008) also found that disciplinary diversity was an important factor in creative scientific research environments. Porac *et. al* (2004) studied the productivity pattern, in terms of publications, of two research teams. One team was monodisciplinary the other multidisciplinary. The findings suggested that the multidisciplinary team was more productive. These studies are all very different, however they do seem to confirm the link

between creativity and interdisciplinary collaboration.

Some other studies looked more specifically at interdisciplinary collaboration, such as Rhoten (2004) who carried out social network analyses and ethnographic studies in interdisciplinary research centres in the US. She subscribes to the idea of interdisciplinary research being a new trend and her findings do confirm that there is a lot of contact between people of different disciplines, however her findings also lead her to question exactly how far the trend has advanced. She describes “co-investigators” in interdisciplinary projects who work in total isolation from each other (2004:6). On the surface such projects appear to be interdisciplinary and their results might be interpreted as being interdisciplinary, but by studying their practice she reveals that some of the general assumptions about how closely different disciplines are working together may not be very well grounded. Similarly to Carayol and Thi (2005), Rhoten also observes a tension between specialisation and boundary crossing. She mentions the nervousness of experienced scientists taking the first step into a new field and the feelings “fear” and “career suicide” (ibid:9) which they express. Reger and Schmoch (1996) carried out in-depth studies of two fields of technology, medical lasers and neural networks. Both fields were described as having multiple applications and requiring collaboration between different disciplines in order to achieve this. Their studies were carried out at several locations in Europe and the methods used were bibliometrics, a study of patents and interviews. Both fields were characterised by the emergence of a techno-scientific community who created a large and diverse interdisciplinary network linking them to experts, industry and sources of funding. (ibid:367). As mentioned initially, they found that some disciplines appeared to be able to work together without obvious problems, those who had problems were the examples of "big interdisciplinarity". They mention that biologists work by systematically collecting observable facts, this (in the case of neural networks) leads to a complex picture of the mechanisms of biological networks. The physicists on the other hand try to achieve adequate models based on a simplification in order to reduce the complexity. This different orientation as well as communication problems and a lack of mutual respect were identified as the greatest challenges to success. (ibid: 363). They observed the “need for better mutual understanding and intense dialogue” (ibid:328) and concluded that this could “only be realised by a deliberate effort” (ibid:364).

In an attempt to understand the role played by mathematical models in the development of interdisciplinary knowledge, Mattila (2005), studied big interdisciplinarity in practice in a laboratory. Mattila's investigation spans the lifetime of the scientific project and describes how participants from different disciplines gradually develop common understandings and how they adapt their ways of working together in different phases of the project. She uses the concept of the object-oriented activity to explore the way mathematicians, computer scientists and medical practitioners contribute to the development of simulation models for infectious diseases. She describes how the research team is composed of people from different disciplines in order to provide the appropriate expertise to develop infectious disease models. Their knowledge practices include a conscious search for common ground and they frequently use colleagues as interpreters and translators. Mattila uses the concepts of complementarity of knowledge and dyads (John-Steiner 2000) to describe the type of collaboration observed in some phases. She suggests that when a shared object of activity is developed, the different disciplines develop new ways of working together. By analysing the changing object she identifies different phases of development and relates this to different ways of working between the different disciplines in the team. She describes interdisciplinary collaboration as being supported and developed by "long, piece-by-piece constructed joint forms of work and practice" (Mattila, 2005:29). Once the shared object had been achieved, there was not the same need for collaboration or for expertise from different disciplines. Mattila concludes that interdisciplinary research work is a fertile ground for scientific discovery.

There is not much data from the evaluation of interdisciplinary research programmes carried out at a micro level, but Bruce, *et al*. (2004) analysed the projects in the 5th EU framework programme. Their analysis was based on data gathered in workshops, questionnaires and interviews with researchers and research managers. Their study identifies many barriers to practising interdisciplinary research. They note, among other things, that the main motivation to collaborate is the interdisciplinary nature of many of the research questions, but at the same time they note that career progression is traditionally associated with specialisation within one discipline. They suggest that interdisciplinary cooperation does not happen by itself, but needs conscious effort to overcome communication problems and promote greater cohesion.

In spite of all these studies there have been few attempts to develop a model of interdisciplinary practice. One of these attempts is the model developed by Klein (1990) which is called the "Integrative Process" (ibid:188-189) and consists three main stages, defining the problem, specifying the various studies to be undertaken and collating all the contributions. Thus leading towards a kind of convergence of knowledge from different disciplines.

Table 1 What we know about interdisciplinary collaboration

General	It has been around for a long time Definitions are not standardised
Extent of interdisciplinary collaboration	Widespread Occurs between many fields of science and technology Occurs in academic and industrial environments
Perceived importance	Contributes to creative solutions, innovative technologies and to the development of science-based technologies.
Challenges	Researchers' careers based on specialisation in one discipline. Funding organised along disciplinary lines. Participants experience communication problems in collaborative projects
Practice	May have differing degrees of closeness in collaboration. May be divided into interdisciplinarity and "big" interdsiciplinarity. Klein's model of interdisciplinary research as an "Integrative Process"

Gaps in our knowledge	We lack detailed descriptions of interdisciplinary practice, particularly "big interdisciplinarity". How are the challenges mentioned above overcome in successful interdisciplinary research projects? Does the way in which researchers work together e.g. how closely they work affect the process of knowledge creation?

This review of micro-studies substantiate some of the broader views on interdisciplinarity, reviewed in the previous section, by providing evidence that communication with different disciplines can stimulate new thinking and in some cases produce measurable results. They also describe the challenges in more detail. We already know that the development of science-based technologies is increasingly dependent on interdisciplinary collaboration (Grupp, 1992; Meyer-Krahmer 1997), but perhaps some studies of groups where the different disciplines are considered far apart, such as biology and physics would give us more valuable insights. The next section presents two recent case studies carried out by the author. The studies presented are of multidisciplinary groups working on technology development. There are two case studies, one in an academic environment and the other in an industrial environment. Both of these cases include examples of big interdisciplinarity, one is biologists and physicists working together and the other is material engineers and biologists. Both of these cases are part of the emerging area of nanoscience and nanotechnologies, an area which has been described as a rapidly developing field based on the convergence of existing technologies. (Roco & Bainbridge, 2001). I am not sure if I agree with the definition of nanoscience or nanotechnologies as *one* or even two fields, however it is evident that techniques for miniaturisation and manipulating matter on the nanoscale have advanced dramatically during the last decade and scientists and engineers from many different disciplines are participating in this development. In keeping with the gaps in our

knowledge identified by the review of earlier studies, the analysis of the case studies attempts to answer the following questions:

How do different disciplines contribute the development of new science-based technologies?

How do researchers of different disciplinary backgrounds learn from each other?

How do researchers from different disciplinary backgrounds create new knowledge and new ways of working?

4. Cases and data

In order to unravel the complexity of interdisciplinary learning, the research design, considered most appropriate, was the case study, which it allowed "how" questions to be addressed such as "How are the participants learning?" The cases chosen are of the instrumental type (Stake, 1994:314), providing the opportunity to study interdisciplinary activities, rather than being representative of a larger population.

All the project participants were interviewed using semi-structured interviewing in order to gain an overview over their roles and tasks in the project. Interviews were recorded and transcribed. All the sites were visited, testing was observed and limited documentary sources were consulted, such as project reports, plans, presentations and emails. These interviews took place over a six-month period, but some supplementary telephone conversations and e-mail correspondence were carried out afterwards.

Interview data on learning experiences is not always considered reliable. In this case candidates were asked to tell their stories about the project work and how the last experiment was carried out. An iterative process was used to follow up learning issues or events mentioned at one interview by analysing the other interview data for different descriptions of the same event. This was compared with data from other participants working on the same experiment. The findings were analysed to produce an overview of instances where learning was thought to have occurred. The socio-cultural approach was then used as a way of sensitising one to the interplay between the heterogeneity of the

participants and their interdependence to identify interdisciplinary processes of knowledge creation.

Thus a description of the gradual development of a new technological solution has been pieced together. Within this mini-trajectory of technological development, examples of interactions between participants from the different disciplines have been identified and analysed in the context of the on-going process. In this way we gain an overall view of the process of technological development and an array of more fine grained instances of interdisciplinary interactions.

The first case (referred to as Case I) is in an academic environment. Contact had been established with an institute recently created by a Nobel prize winner. His aim was to build up a new multidisciplinary research institute dedicated to studying nanotechnology and supra-molecular structures. Initially the directors of five different laboratories, within the same institute were interviewed. It was found that only three of these were multidisciplinary i.e. had employees who were educated within different academic disciplines. More interviews were carried out within these three laboratories and their strategy documents, descriptions of on-going projects and funding applications were consulted. Within these three multidisciplinary laboratories it became evident that there was one lab where the participants considered themselves to be very dependent upon each other and they worked very closely together. This lab also consisted of physicists, biologists, chemists, electronic engineers and biochemists, thus meeting the criteria above and also providing an example of "big interdisciplinarity". This lab was also willing to be interviewed and allow an external researcher into their laboratory. In addition to the criteria, the apparent openness of the people working in this lab suggested a good opportunity to learn from this case. So although this case may not be typical or representative of interdisciplinary collaborations, the opportunity to obtain detailed descriptions of their work over time and learn from the case were a deciding factor in the selection of this case.

The second case (Case II) was in an industrial setting where access is traditionally very difficult. There are typically issues of confidentiality, patent protection and company secrets; therefore the choice of case is often effectively limited by availability or accessibility. The process of finding this case was rather different. Information on nanotechnology R&D

projects receiving public funding in the UK was used to identify potential cases. Thereafter some national experts in technology incubation and the chemical industry were consulted. Their knowledge of the participating firms was used to narrow the list and they also acted as door-openers to several projects. Eventually the case was chosen because it met the above criteria for an interdisciplinary R&D project within nanotechnology and because the participants were, albeit reluctantly at first, willing to give an external researcher access to project information. The case chosen was an R&D project in the UK, which received public funding and sponsorship from the industrial actors participating in the project. This project consisted of material engineers and biologists. There were certain restrictions on access or use of data from this case, due to the competitive nature of the product. [1] As in the first case the opportunity to learn from this case were estimated to be high. Again it may not be typical of a multidisciplinary industrial R&D project, however the enthusiasm of the participants to share their discoveries provided an opportunity to gain a good understanding of how the knowledge creation process developed during the project.

Table 2 Cases

Case	Location	Nr. of participants	Disciplines involved	Technology under development	Potential applications
I	France (Strasbourg) with contacts in US (Harvard)	16	Physics, biology, chemistry	Microfluidics technology	Medical diagnostics, Pharmaceuticals, detection of chemical contamination

[1] One of the partners was a European subsidiary of a US corporation and their patent lawyers were very nervous about my presence, but fortunately the scientists and engineers participating in the project had a much more relaxed attitude.

II	UK (6 locations in South East England)	9	Material engineering, chemistry, biology	Nanomaterial technology	Anti-viral preparations integrated into artefacts in hospitals, aircraft etc.

These cases are described in more detail in Olsen (2009a, 2009b, 2010), only a summary of the findings is described here.

5. Discussion of findings

The findings are divided into two groups relating to contributions of interdisciplinary research and learning between disciplines.

5.1 How have the different disciplines contributed to the development of these science-based technologies?

As mentioned (2.&3.) earlier research has suggested that disciplinary diversity provides a positive contribution to research projects. The work reviewed suggested that interactions with researchers of another discipline are the way in which these interdisciplinary contributions arise. Apart from references to interaction and proximity, these studies do little to describe or discuss the ways in which such contributions are made. The two recent case studies, however, indicate that the multidisciplinary research teams studied did indeed make contributions to the research projects, and they did this in a variety of different ways, thus contributing to the development of microfluidics technology and anti-viral material technology. Four different ways of contributing were identified. The first was creative problem solving. This occurred on an everyday basis and solutions were found based upon different theoretical perspectives, different methods and concrete experience gained in a different field. For example in Case II, (Olsen, 2009b). material engineers refined their choice of metals to be tested based on the biologists suggestions about virus behaviour. In Case I, (Olsen, 2009b), when new ways of testing were needed, physicists suggested ways of adjusting the technology, while the biologists and chemists suggested alternative adjustments based on their knowledge of cell behaviour. These options were discussed

before a decision was made. Thus the cases discussed here support earlier findings of contributions in terms of creative solutions, from a wider variety of perspectives and approaches from multiple disciplines.

The second way of contributing was more indirect and was observed in situations when people in one discipline ask colleagues in other disciplines for help or where they simply make assumptions about what the other discipline knows and give them a task. In Case I (Olsen, 2010), the biologists ask a physicist to design a new device, the biologists get a new device and a whole host of new research results from it, while the physicist inadvertently finds a new kind of nanoparticle. In Case II (2009b), the material engineers just assume that the biologists can test their samples in a certain way, this produces a conflict initially, but ultimately results in adapting their ways of testing and expanding the kind the tests done. These examples resulted in contributions to the research projects. Most of the incidents recorded are of the incremental type where an obstacle was overcome and the existing ways of doing things were expanded to include a wider range of samples, alternative ways of testing or faster ways of producing results. The discovery of the new nanoparticle is the only example of a potentially far-reaching contribution. The type of interaction whereby one part makes a request, or a complaint, is recognised as contributing to product innovations (von Hippel 1988), but to my knowledge this mechanism has not been linked to interdisciplinary collaboration before and thus represents a new contribution to our understanding of the way in which collaboration between different disciplines can influence technological development.

It is not only contributions to the day-to-day practical work in the lab where the influence of interdisciplinary collaboration can be seen; the third type of contribution identified was to the evolving research agenda. This was something, which Rhoten (2004) found in her survey of researchers working in multidisciplinary collaborations. 83 percent of the researchers said that their relationships to researchers from different centres (i.e. different disciplines), had influenced the development of their research agendas in a positive way (2004:9). The studies presented here support Rhoten's, in that changed research agendas are indeed one of the contributions of interdisciplinary collaboration, however unlike earlier studies the ones presented here provide a detailed description of how these agendas are changed and indeed how they continue to change. In Case II (Olsen, 2009b), the material engineers move from

their original idea of constructing a material barrier to block the influenza virus, to designing a material which could provoke change in the virus and thus deactivate it. The latter choice is based upon theories of virus behaviour developed by biologists and would not have been an alternative for the material engineers, had not biologists been involved. The historical development of microfluidics technology, as described in Olsen (2010), provides an overview of the changing research agenda over time and describes how the meetings of physicists, chemists and biologists at different times have influenced research agenda.

The fourth way of contributing relates to the use of scientific instruments from another field. Previous research has suggested that scientific instruments play a role in the spread of knowledge between different disciplines (this research is described in more detail in Olsen 2010). These instruments have been defined as a vehicle for communication of technological knowledge (Fujimura, 1992) and it has been suggested that they promote a kind of ligua fanca between different groups of scientists (Shinn, 1995). The studies presented here provide examples of how instruments from one scientific field are used in another and support the idea that technological knowledge is communicated from one discipline to another in this way. My studies, however, go further than those reviewed in that they show how the use of scientific instruments is integrated in activities and how this combination of instruments and activities contributes to the development of microfluidics technology. The main finding is thus a more nuanced understanding of how the interplay between instruments and research activities develops and produces different outcomes, according to whether they are used as originally intended, differently, producing different outcomes, or deliberately adapted. I found that, albeit indirect, these are all ways in which multiple disciplines may contribute to the creation of new technology.

The focus in this paper has been more on the on-going processes rather than the outcomes. The empirical data in the two case studies indicates that the projects studied have made progress and have indeed developed new working technologies, even although the outcome in terms of publications and patents has not been measured. So although not directly comparable with much of the earlier research on interdisciplinarity, the cases here suggest support for earlier findings on the relationship between disciplinary heterogeneity and creative solutions in research projects. More importantly the findings presented here go further than earlier research by attempting to identify the ways in which the different

disciplines contribute to the development of new knowledge and new technological solutions concluding that the contributions of different disciplines can range from everyday problem solving, to changing the research agenda.

5.2 How did researchers of different disciplinary backgrounds learn from each other, create new knowledge and new ways of working?

In this section interdisciplinary collaboration will be considered in terms of knowledge processes and the research projects as learning environments. The findings are divided into two categories which have emerged from the data gathered in the two cases:" intertwined processes" and "taking short-cuts".

5.2.1 Intertwined processes

One of the questions which has been raised about interdisciplinary research is how much contact there really is between different disciplines (Rhoten, 2004) and we would expect the amount of contact to influence the way in which people learn from one another. This issue has been examined more closely in the case studies presented here and one process identified was where intensive cooperation was found between small groups of people from two disciplines. In Case II (Olsen, 2009b), this happened in the early stages where one material scientist worked in a biology lab one day a week for a whole year in order to learn their testing procedures. In Case I there appeared to be several cycles whereby people from two disciplines worked closely together for some time until a routine became established. An example of this is the production of devices for use in the microfluidics station (Olsen, 2009a). Once a routine became established it was possible for one discipline to withdraw from that activity.

In addition to these findings there was evidence that many participants had learned more about how to communicate and behave with people of a different discipline, indeed to such an extent that they could manoeuvre within the other discipline participating in conferences, publishing and gaining funding for their work. Not only had participants (in Case I) learned how to manoeuvre within a different discipline, but they had also created an environment where it was acceptable to be both a novice and an expert at the same time. (Olsen, 2009a:404).

5.2.2 Using mediators to take short cuts

Another aspect of interdisciplinary collaboration which wasidentified in some of the studies reviewed section 3 is the importance of objects or people as mediators in the knowledge process. Mattila suggests that colleagues can be used as translators and interpreters giving a kind of limited access to the knowledge and experience gained in a different discipline. This suggests that an important aspect of successful interdisciplinary collaboration is the ability to identify and use the knowledge resources of a colleague. This may be particularly important in situations where contact between participants is not constant and may be of limited duration.

In the two case studies, the use of colleagues as mediators was found in both cases. In Case I the physicists enabled the biologists to use theory from fluid physics to prove the reliability of microfluidics, without having to understand fluid physics. Many examples were observed during problem solving where alternative suggestions came from different disciplines and were adopted without everyone understanding the theory behind them. In Case II (Olsen, 2009b), the main mediator was the engineer who had spent a long time working with biologists, he functioned as a translator and found other appropriate forms of mediation in terms of conceptual tools. Perhaps the most important feature of using colleagues as mediators is that an external field can be accessed quickly. Thus finding the right colleague is a kind of short-cut. This way of working is not new indeed Lundvall (XXXX) refers to knowing the right people or "know-who" as an important ingredient in the learning economy, however in the cases studied here it is made visible as an important mechanism of knowledge creation in interdisciplinary research collaboration.

This brings us to another important aspect of finding short-cuts and that is using and developing common conceptual tools or models. In Case II (Olsen, 2009b), this was identified, when the material engineers' model was expanded to incorporate "anti-viral" as a property thus making it possible for the material engineers to accept an unfamiliar biological phenomena without understanding it fully. They understood it as a property of a material, like all other properties such as flexibility, magnetism etc. Once "anti-viral" had been classified within the models of material engineering it was possible for the whole group to move on and find solutions. In Case I (Olsen, 2009a), it mathematics in the form of equations which become the shared format. The physicists asked the biologists to describe their

experiments in terms of equations. This made it possible for the physicists to suggest ways of improving the experiments without needing to understand all the biology.

This idea of building bridges between and within heterogeneous groups, is not new and indeed is similar to the concept of boundary objects, defined by Star & Grisemeyer (1989). It has also been identified in studies of knowledge integration, Carlile (2002). In this respect the findings of the current study support earlier findings

Another form of short-cut is finding and developing physical tools or in this case scientific instruments from another field. Despite the importance of scientific instruments in the development of science-based technologies, there has been scant attention paid to their role in studies of interdisciplinary research. As mentioned earlier both Shinn (1995) and Fujumura (1992) recognise the potential of instruments in the knowledge creation process and Fleck (1997) confirmed the importance of not just acquiring tools from another field, but also of adapting them for use in the local context. The cases presented here examine the process of bringing in technology in the form of tools and instruments from other fields and further developing them. This is particularly evident in Case I (Olsen, 2010). During the process of using and adapting the different tools and instruments the group make significant progress in their understanding of the microfluidics technology and greatly enhance the efficiency and the variety of applications for the technology. Indeed the whole field of microfluidics would never have come into existence, had not chemists taken tools and techniques developed in microelectronics and made them their own by pouring liquid through microchips. The different interdisciplinary learning processes identified in these cases are summarised in the following table.

Table 3 Interdisciplinary learning processes

Process	Example from case	Case
1. Intertwined practice	Physical co-location, discussing work and developing a common object	1 & 2
	Intertwined practice, shared tasks, working	1

	closely together	
	Adapting tools and instruments from different disciplines	2
2. Mediated Short-cuts	Transferred practice based on codification and common conceptual tools	1
	Using conceptual tools to build bridges between concepts	1 & 2
	Relying on a trusted colleague or go-between	1 & 2
	Learning by using tools, based on knowledge being encapsulated in the tools	1

Table 3 suggests that there are different ways of learning from another discipline and that some of it requires only limited time and effort (Process 2). This may be the case, however, if we look again at the processes over time rather than just these individual incidents, we get a glimpse of a possible pattern. We can see that the examples, which I have called short-cuts, were often preceded by a longer period of close cooperation between two or more people from different disciplines. In Case I the biologist who built his own microfludics station, seemingly without understanding any of the physics involved, had worked closely with the physicists on a variety of tasks for many months prior to this event. Similarly in case II one of the material engineers had worked closely with the biologists for one year. I suggest that the period of working closely together made it possible for a person from one discipline to build up the necessary trust to be able to rely on colleagues from another discipline, the necessary knowledge to be able to identify who-knows-what in the other discipline, and to understand how to communicate and how to behave in the other discipline. This experience has given them an important basis for the role of mediator, which both cases exhibit and a starting point for finding other short-cuts.

These findings of how people learn or how they learn from each other while working together (Table 3) are not new, however it is when these learning processes are used to understand interdisciplinary collaboration that we gain new insights.

Furthermore it gives us a better understanding of the order in which different activities may occur, i.e. that the slow intertwined process identified in both cases may provide the basis for other types of collaboration which may then proceed much faster by using a mediator to access what is needed from the other discipline or by formulating a request in a way which will be understood by the other discipline. The following figure (Figure 1) attempts to present this idea, by summarising the different types of interdisciplinary collaboration, which might lead to the successful development of new technologies in spite of the distance between the disciplines involved.

Figure 1 Interdisciplinary collaboration in practice

<table>
<tr><td colspan="2">Intertwined Practice</td></tr>
<tr><td>Gradually developing over time in small groups or dyads</td><td>Leads to deeper understanding of part of another discipline. Makes it possible to identify means of mediation</td></tr>
<tr><td>↓</td><td>Provides opportunities for taking</td></tr>
<tr><td colspan="2">Short cuts</td></tr>
<tr><td>Identifying the potential in a knowledgeable colleague, a conceptual or physical tool & utilising him/her/it</td><td>Provide access to relevant:
• Historical experience
• Practice
• Tools
• Theories</td></tr>
</table>

This figure summarises the learning processes identified and discussed in the previous paragraphs and links them together by suggesting that the intertwined process precedes the finding of short cuts. Thus the figure provides a way of conceptualising interdisciplinary collaboration.

Seen together Table 3 and Figure 1 provide an overview of interdisciplinary collaboration in practice based on the findings of the two case studies and the literature review. These processes suggest different ways in which interdisciplinary collaboration might result in knowledge creation and can thus be viewed as sub-processes occurring within interdisciplinary collaboration. Instead of using the general term interdisciplinary collaboration to refer to situations where people attempt to work together to produce new knowledge, it is now possible to refine the concept of "interdisciplinary collaboration" and refer to different processes occurring within this kind of collaboration. This awareness of the different ways in which people of one discipline may gain access to each other's expertise fills some of the gaps identified in Table 2.

6. Implications

These can be divided into three different areas of interest; the implications for our understanding of "Big interdsiciplinarity", our understanding of interdisciplinarity in general and the potential implications for practising interdisciplinary resarch.

6.1 Implications for our understanding of "Big Interdisciplinarity" in the development of science-based technologies

Both these cases and some of the studies reviewed (Mattila, 2005), provide examples of how multidisciplinary groups of researchers with backgrounds in widely different disciplines have developed ways of working together and how they are achieving their aims of developing new technology. Thus the very existence of these cases and their current success confirms that, in spite of some conflicts, "big interdisciplinarity" (i.e. collaborations where the disciplines the participants are educated in, are considered far apart from each other) is alive and flourishing in an academic and an industrial setting.

The findings of the two case studies confirm some earlier findings about the challenges of interdisciplinary research and provide examples of those found in "big interdisciplinarity" (Reger & Schmoch, 1996). However this study goes further in that it suggests some explanations for these challenges. The findings suggest that one of the reasons interdisciplinary research is often slow and difficult is that there is a need for a gradual learning process, involving joint participation over a period of time (Intertwined Practice, Figure 1). However this study also suggests that not all participants need to develop in-depth

knowledge of the other discipline. There are lots of potential short-cuts (See Figure 1). Therefore we can say that not all multidisciplinary tasks require much learning from another discipline in order to be carried out in an effective way. We can also say that much of the work involved in developing the science-based technologies studied here, while requiring the knowledge and skills of more than one discipline, can actually be carried out with only limited contact and limited learning between the disciplines.

These findings may have some implications for research policy designed to encourage different disciplines to work together in networks and consortia. This collaborative research may not result in learning between disciplines. We cannot assume that this happens automatically and it may require a prolonged period of close cooperation.

6.2 Implications for research practice

An awareness of the potential of taking short-cuts may be useful for managers of interdisciplinary research projects or institutes. By deliberately searching for common entities, such as shared formats, instruments and by ways of developing a common platform, managers might find ways of making big interdisciplinarity more cost-efficient. Another potential tool in the managers' toolbox is the possibility of implementing overlapping work for a limited number of participants. This might make it easier to bridge the gap between disciplines without everybody having to become experts in the new discipline. Lastly the importance of creating an environment where expertise is prized at the same time as experts are novices in a new field is something which research management ought to consider particularly in cases of big interdisciplinarity.

6.3 Implications for our understanding of interdisciplinarity

Some of the better-known works on interdisciplinarity suggest that knowledge from different disciplines needs to be integrated in order to be useful (Klein, 1990; Hansson, 1999). However my findings suggest that a great deal of useful knowledge including technical know-how is being generated without the participants gaining a deep understanding of each other’s field. It would appear that technology which requires the contribution of people from different disciplines in order to make it work, does not necessarily require that this knowledge be integrated.

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