Connecting Different Disciplines to Develop New Technology: making nanomaterials to combat bird-flu

Abstract

R&D in nanosciences and nanotechnologies (NST) has been characterised as a multidisciplinary effort (Meyer & Persson 1998) or as convergence of knowledge (Roco & Bainbridge 2003; Nordmann 2004) Scientists and engineers face the challenges of integrating knowledge from different fields in order to create something new. This paper investigates an R&D collaboration aimed at developing anti-viral nanoparticles and incorporating them into various products. The paper takes a socio-cultural approach to the collaborative development of knowledge (Engeström 2001) The findings suggest that that there are many different ways of learning from other disciplines and they provide a supplement to our existing understanding of knowledge creation in multi-disciplinary environments.

Keywords: interdisciplinarity, learning, R&D projects, nanomaterials

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1. Interdisciplinary Collaboration in R&D

Recent discourse on knowledge production in science and technology (Gibbons et al 1994) suggests an increasing need for different scientific disciplines to work together in order to advance knowledge in these fields and to contribute solutions to modern problems such as energy, health and environmental problems. Meyer-Krahmer (1997;1998) and Reger and Schmoch (1996) highlight this particular challenge in relation to new science-based technologies such as nanotechnology. R&D in nanosciences and nanotechnologies (NST) has been characterised as a multidisciplinary effort (Meyer & Persson 1998) or a convergence of knowledge (Roco & Bainbridge 2003; Nordmann 2004) Scientists and engineers working in this field have themselves suggested that developing interdisciplinary skills is one of the greatest challenges to development of new products and processes in NST. (Nanoforum Report, 2004:61) Although not all NST requires interdisciplinary collaboration, cooperation between scientists of different disciplines, engineers and medical personnel is a common occurrence. The increasing need for different disciplinary perspectives on technological problems and different skills required to solve them suggests that a better understanding of processes of interdisciplinary learning could be an important contribution to managing R&D and to our understanding of the challenges facing the development of NST.

Studies of technological development and innovation have addressed the issue of "interdisciplinarity", but this has largely been concentrated on assessing the extent of interdisciplinary collaboration (van Leeuwen & Tijssen; 2000; Schummer, 2004) or mapping who is collaborating with whom, viewed at a macro level (Leydesdorff & Rafols, 2008; Valentin et. al., 2008) As yet there has been a limited amount of empirical research which actually tries to understand the processes involved in collaboration between participants of

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different disciplines in order to produce technological knowledge. In R&D projects in science-based technologies many participants will have received their training within different academic disciplines, these disciplines have developed over time and that have their own languages, traditions, institutions, codes of practice and ways of working (Becher, 2001) and we would expect the participants to bring these different ways of working and ways of thinking, with them, into R&D projects. Any study wishing to understand how disciplinary diversity might affect knowledge creation in R&D projects, should not ignore the importance and the potential influence of the disciplinary histories and traditions. Therefore one of the aims of this paper is to provide some descriptions and analyses of the types of learning processes occurring when different disciplines collaborate in R&D projects and thereby supplementing existing knowledge on learning in R&D projects.

2. Collaborative learning and co-creation of knowledge

This section outlines some of the different perspectives on collaborative learning relevant to industrial R&D. Knowledge creation has often been viewed as the integration of knowledge supplied by the various specialists and is seen as a prerequisite for successful cooperation between participants (Grant 1996). Some of the traditional views of organising and coordinating activities leading to knowledge integration are summarised by Grant (ibid) as rules, sequencing, routines and group problem solving. These mechanisms assume that most the differences between participants are stable, visible and known, that they just need to be organised in the right way so that transfer can take place. This may be the case if one is merging two different databases, however there are few guidelines on how to cope with anything new or unexpected. Grant recognises the limitation of these traditional views and adds to them by including the importance of common knowledge.

Similar concepts are highlighted by other studies of R&D projects (Enberg et. al, 2006; Kreiner, 2002). Here the reservoir of tacit knowledge, based on previous experience, plays an important role in negotiating project objectives and in coordinating divergent processes. Thus an awareness of this tacit foreknowledge and an ability to utilise it become means for diverse participants to learn from each other, and to develop new knowledge in R&D projects.

The particular challenges influencing knowledge creation in temporary project organisations have been addressed by Lindkvist (2005), who uses the concept of the knowledge collectivity to describe projects where people of different disciplines or functional departments come together to develop new products. These projects typically contain an element of exploration and the type of knowledge development process Lindkvist implies is a goal-directed process, which draws the different participants together. Knowledge collectivities also rely on high levels of “know who” i.e. knowing the capabilities of one’s colleagues and they have a strong dependence on trial-and-error type of feedback. “The extensive use of milestones, practical testing and other feedback measures, here means a preoccupation with error or failure signifying a need to continuously monitor what actually works or not” (Lindkvist 2005: 1202). This perspective reveals a wide range of ways whereby the various participants can contribute to the development of an integrated product.

These perspectives on collaborative knowledge creation can be summarised thus:

Main focus	Author	Means
Coordination and integration of knowledge from diverse specialists	Grant 1996	Rules, sequencing, routines & group problem solving Common knowledge
Integrating knowledge	Enberg et. al 2006 Kreiner 2002	Utilising tacit foreknowledge
Temporary project organisations (Collectivities)	Lindkvist 2005	Goal-directed Know-who Feed-back

Table 1 Perspectives on collaborative knowledge creation

All these perspectives are relevant to the theme of collaborative learning and they all address the issue of heterogeneity among participants. However, to view multidisciplinary R&D as a matter of accessing the right resources or simply a matter of coordinating the integration of data from two different domains is to underestimate the complexity of multidisciplinary R&D. Since we are investigating R&D, we must assume a certain amount of explorative R and an unpredictable path of D until the final product is achieved. Nanosciences and nanotechnologies are not yet well understood and in many cases the technology is developing before the “underlying” science. We assume that this is not just a case of sharing knowledge between different groups of researchers, but that some new knowledge will also have to be developed; they will have to solve new problems, find new ways of doing things and develop new techniques. In this case theories of knowledge integration based on the information processing models are less relevant. Although the concepts of knowledge collectivities and tacit foreknowledge both give valuable insights into how diverse participants work together they do not fully address the interplay between the, often individual, disciplinary training and collaborative learning in R&D projects.

The socio-cultural perspective will now be introduced, with the aim of supplementing or further developing these concepts. Proponents of the socio-cultural approach talk of expansive learning (Engeström, 2001) and co-creation of knowledge as a collaborative process with participants often from several different environments. This perspective recognises that there is an element of exploration and creation of new knowledge and new practices (expansive learning) rather than just exploitation of existing knowledge. According to Engeström (ibid) one should not simply take the view of the collective, homogeneous subject (the participants in the R&D project), one should instead treat the subject as heterogeneous or as having different “voices” which come together and contribute to an activity. In order to understand what is going on in an R&D project we should move between the collective system view and the views of the individuals embedded in systems. This concept of multi-voiced activity has been used to study communication and creation of new meaning between different cultural groups (Gutierrez et. al. 1995) and to study cultural and disciplinary diversity in academic research projects (Akkerman et. al, 2006).

3. Research Design and methods

One of the aims of this research is to unravel the complexity of interdisciplinary learning. The research design, considered most appropriate, was the case study, since it allowed "how" questions to be addressed such as "How are the participants learning?"

All the project participants were interviewed using semi-structured interviewing in order to gain an overview over their roles and tasks in the project. These were followed up with new interviews directed more specifically at learning. Interviews were recorded and transcribed. All the sites were visited, testing was observed and available written material was used. 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 and documentation for different descriptions of the same event. This was compared with data from other participants working on the same experiment and supplemented with written sources, such as project reports, plans and presentations. The socio-cultural approach was used as a lens through which to view the findings. They were analysed to produce an overview of instances where learning is 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.

4. R&D in advanced materials

Traditionally the production of materials was dominated by bulk materials such as steel where the producers could exist without much contact with the various users of the product. However recently there has been an increase in what has been called functional materials (Cohendet et. al. 1988) These functional materials are typically produced in smaller quantities and tailored for a particular type of usage or end-product. The development of functional materials is typically carried out in a close cooperation between users and producers. Collaboration is typically with a client, although it is not unusual for to have links back to suppliers.

As well as influencing who participates in R&D, the move to functional materials has also resulted in a move away from viewing the field in terms of *which material* one works with e.g. polymers or metals, but more of managing and exploiting the relationships between material properties, structure, processing and performance, regardless of material type.

Figure 1 shows a typical conceptualisation of materials used by material engineers.

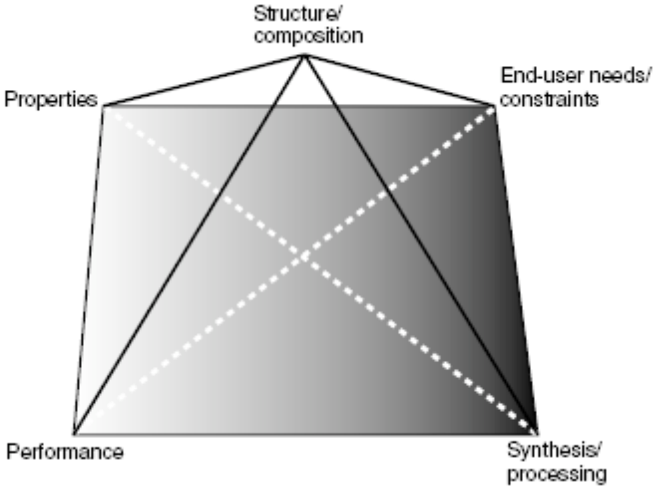

Figure 1 Graphical representation of the common elements in the material science and engineering discipline (independent of material type) US National Research Council (NRC 1999)

Although material science and engineering (MS&E) has been around for a long time as a discipline and uses well developed and documented theories from metallurgy and chemistry among others, like all technology it faces the ultimate test that it must work (Vincenti, 1990). In response to the increasing customisation of materials, there is an increasing involvement of users in R&D projects. The high-speed nature of modern product development in this field is resulting in and increased reliance on high-speed testing of alternative solutions to find combinations which work. (National Research Council, USA, 1999) This testing often precedes the development of formal theory and is often the only way to develop solutions as all the theory is not always known in advance.

5. Case

This case is a project comprising of participants from two universities, two multinational corporations (MNC) and two small companies (SME). They receive mainly public funding from a local regional development fund in the UK. The background for the case is based on the work of a material scientist at University-QM. While in China during a SARS outbreak he became aware of limitations of the traditional facemask in preventing the spread of viruses, which were so small that they could pass through the textiles. On his return to the UK he started looking for a material, which might be used to improve the functionality of facemasks in preventing the spread of viruses. Initially he had little success but when he tried nano-sized particles of the same materials his results were much more promising. Around this time he teamed up with a SME-Bio, a university spin-off who had their office in the same building. SME-Bio were biologists who specialised in the production and testing of vaccines and their director is considered to be a national expert on influenza and pandemics. The material scientist from University-QM worked closely with the biologists, used their laboratory and learned a lot about viruses and some of their testing techniques. He ended up with nano-particles of several different organic materials, all of which had anti-viral properties i.e. they could de-activate a virus on contact.

The material scientist wanted to continue the work and contacted the CEO of a local SME (SME-NanoMat) who was visiting the university. After several meetings where the director of SME-Bio endorsed the "discovery" of the anti-viral particles and their potential in the event of a bird-flu pandemic, SME-NanoMat agreed to get involved. SME-NanoMat was a spin-off from a defence technology company and consisted mainly of material engineers who produce nanoparticles using their own patented method. SME-NanoNat was well connected and managed to bring valuable partners to the group. They brought in a material science institute at University-B, who were willing to characterise the particles and to try and develop a new process for incorporating the particles into or on to a surface coating, MNC-ChemMat who are specialists in functional materials and coatings and were willing to try and develop an alternative coating process and MNC-Manu, an industrial manufacturer, who was willing to try the new coatings on some of their products. This project was a new constellation of participants and only the CEO at SME-NanoMat actually knew all the participants.

5.1 Project Organisation

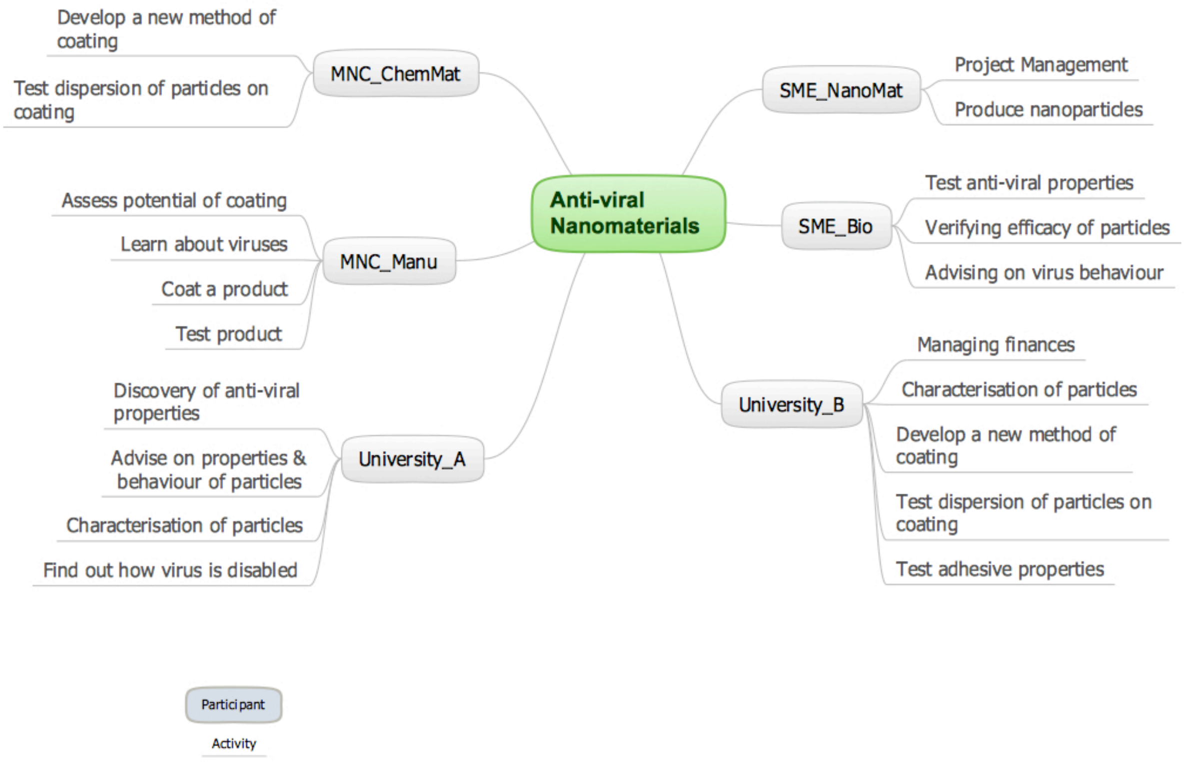

Figure 2 Project Organisation

Together they managed to secure public funding for a one and a half year project to develop anti-viral materials to deactivate the avian influenza virus H5N1. SME-NanoMat provided the project manager. They had several meetings to agree on their mandate thereafter they held monthly telephone meetings and quarterly project meetings where they met a one of the participants' offices.

As the Figure 2 shows, the various tasks in the project were divided among the participants and there was little overlap in the content of these tasks. There was however an overlap in terms of time and many of the tasks were carried out in parallel, as shown in Figure 3. This is a frequent feature in modern product development projects and is described by Lindkvist et. al. as the "fountain method" (1998) as opposed to the traditional "waterfall method". This means that the process of producing nanoparticles was still being optimized while the processes for incorporating the particles into a coating were being developed and many changes were being carried out after the testing had started.

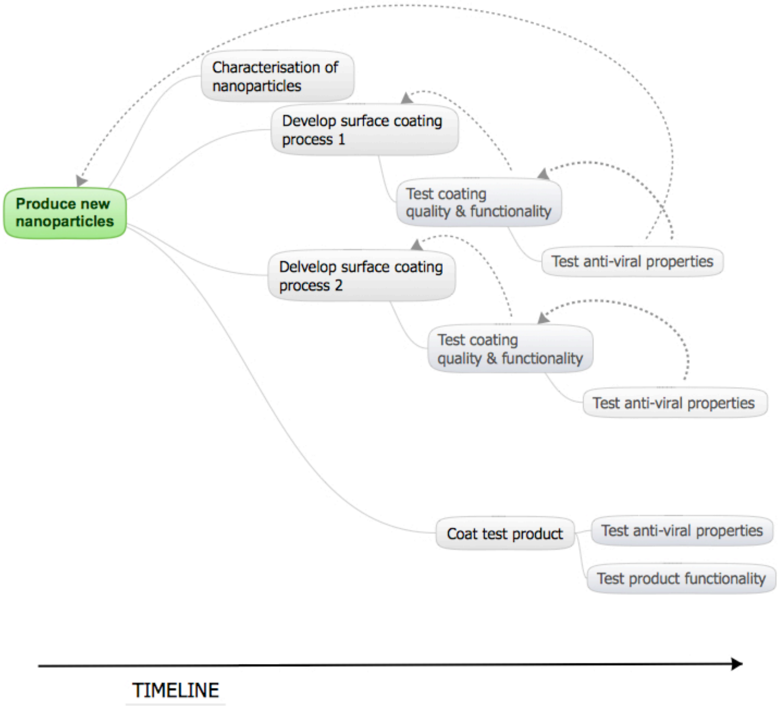

Figure 3 Parallel processes

A summary of the findings is presented in the following section.

6. Learning and knowledge creation in the project

Here the term "learning" is used to describe situations where new knowledge has been produced, where participants have gained a new understanding and situations where participants have succeeded in developing a skill or a technique that they did not have before.

Ex	Who learned	What did they learn	Type of learning	No. of Disciplines involved
1	Material engineer and biologists	Potential of anti-viral particles to combat flu.	Close collaboration at the same location doing the same activities over time	2
2	Material engineers and biologists	Developed a common vision for the project	Translations and discussions at meetings	2
3	Surface coating teams of material engineers. University_B & MNC_ChemMat	How materials can potentially disable viruses	Sharing of explicit knowledge, mediated by conceptual tool	2
4	Material producers SME-NanoMat	How to produce the new nano-particles	Specifications from inventor and adaption of existing procedures	1
5	Material producers SME-NanoMat	How to optimise particle production	Trial and error; testing and adaption of parameters of existing process	1
6	Surface coating teams of material engineers. University_B & MNC_ChemMat	How to incorporate new particles into existing coatings	Adjustment of existing “templates” supported by trial and error testing	1
7	Surface coating team, University_B	How to test that the particles will stick to the surface	Adaption of a previous testing techniques using a nano-indentor machine	1
8	Biologists (from Material Engineers)	How the physical properties of materials can influence the virus	Conversations, sharing of explicit knowledge and testing	2
9	Biologists	How to test new materials	Adaption of existing test protocols supported by trial and error testing	1
10	Material engineers	How to prepare test samples for biologists	Process of formal communications followed by negotiation	2
11	Material Engineers	How to interpret test results from biologists	As above	2
12	Biologists	How to “fit” testing in with the engineers practice	As above	2
13	User firm (MNC_Manu)	Who knows what	Interaction. Gained new understanding	2

Table 2 Learning in the project

It is interesting to observe that in many of these instances of learning, only one discipline is involved. The instances where more than one discipline is involved will now be analysed in more detail. Some of these instances might be classified as knowledge sharing, while others show creation of new knowledge.

6.1. Developing new understanding by close collaboration

Before the project started the material scientist who was investigating which nanoparticles might have anti-viral properties, worked at the biologists' lab for a year.

We were all interested in making face masks, I had some materials I thought would work, but I needed to test them.

I learned a lot about how the virus behaves and how it interacts in a way with the material

“*We talked a lot, I watched them and they trained me to do the basic tests*”

“*He (Material Engineer at University QM) explained about the materials and their properties, what was possible and not possible to do with materials. We adapted our tests for him”(Biologist in SME-Bio)*

This slow process resulted in a common understanding of the potential of particles, especially in the event of influenza pandemic.

Stage 1	**Biologist's original object of enquiry**: To develop vaccines to protect against avian influenza *Becomes* ↓		**Material engineer's original object of enquiry**: To find a material that would prevent small viruses passing through face-masks *Becomes* ↓
Stage 2	**Common object of enquiry**: to make an anti-viral nanomaterial for use in a future avian influenza pandemic		

Figure 4 Development and expansion of the object of enquiry

Armed with this common vision and the ability to “translate” it for biologists or material engineers, they moved out of the lab in search of partners to fund and further develop their findings. This close collaboration is similar to the intertwined practice observed in multidisciplinary laboratories (Olsen 2007). This looks like an example firstly of successful knowledge sharing, followed by the co-creation of the common object of the research project. This is also typical of expansive learning (Engeström, 2001) and includes questioning, analysing, modelling a new solution, or in this case testing it. The result of this process was that both partners had a common understanding of the potential of these new particles to disable in the flu-virus in various material applications. Both partners also realised that it was not possible to continue without involving more partners to develop solutions and of course investors.

6.2. Using conceptual tools to share develop new understanding

At the beginning of the project all the participants met and University-QM and SME-Bio presented their findings and presented their views on the future potential of these findings. The material engineers at University-B and MNC-ChemMat immediately started asking questions about the new particles and their properties. During that meeting both decided how they were going to proceed.

> "*I knew that we needed to put the particles on top of the coating in some way. I wasn't really sure how we would do it, but it just seemed natural to me that we should do it that way. We always consider the properties of the material and how the environment has to be for it to work. These particles needed exposure to the air and that was the most important thing to achieve, otherwise they are just like any other particle and we have tests and procedures for testing them." (University-B)*

By the end of the first meeting MNC-ChemMat had a similar idea of what they would do with the particle.

Both these groups of material engineers were able to see the similarities between these new particles and previous material development projects they had worked with. They knew which questions to ask, what new features they should look for and were quickly able to classify the new challenge in such a way that they could make it manageable. It was neither necessary for them to make detailed plans of the next stage nor to spend time designing, before they started to make the new surface coating. In this case the integration of knowledge from another discipline represented no particular challenge and the material engineers were able to continue to the next stage of developing coatings with little or no contact with the biologists. It was natural for them to use the conceptual object of modern functional materials (see Figure 1). This is an example of learning mediated by a conceptual tool. This made it possible for the engineers to absorb and use this knowledge in a fruitful way, without actually understanding all the biology behind the anti-viral particles and without knowing very much about bird-flu.

6.3. Learning by reflecting on and adapting existing practices

The two groups (University B and MNC-ChemMat) worked separately and sent samples SME-Bio and received results from them. Many participants experienced problems relating to the anti-viral testing, i.e. testing the efficacy of the material to de-activate the virus. This required a division of labour, which the material engineers were not so familiar with, they were unable to build, test, adapt, test etc as they would normally do when adding a new component to a coating in this way. Instead the samples were sent to another location.

Material engineers talking about the anti-viral testing:

> *"The anti-viral testing is the most important part of the project. It is probably the main thing that is questionable about moving forward. We need to have a particle, which we know is effective and we need to test loads of samples"*

> *"It all hangs on the reliability of the test results. I think these tests are quite difficult to set up. I don't know how routine they are."*
>
> *"It all comes down to the anti-viral testing. I'm not really sure what these tests are.* ***They*** *say what they consider is good or excellent.* ***We*** *really need to know how long will the particles remain active? Does the dispersion of the particles on the material affect the efficacy? Are certain particles sizes or shapes better than others? We just don't get enough detailed information back from the testing"*

Biologists, talking about their role as experts in testing:

> "*Normally when we work with clients they tell us what they want to test for or what they want to prove, we suggest how this should be tested. We have an advisory role and we always have a dialogue with our clients."*
>
> *"Fundamentally its all about reliability, you know, can we reliably repeat the tests and get the same results? We need that for our accreditation"*

Biologists talking more specifically about the bird-flu project:

> *"Our role is just to prove that it works or it doesn't work, the biggest thing is explaining how it works, that's outside my area"*
>
> *"They want us to test everything. They send us 200 samples at a time. They need different set-ups and it can take 2-4 weeks to test one sample.*

A typical way of learning for the engineers would be to design a test, create it, monitor results, adjust, re-test, adjust, re-test etc. This pattern is being disrupted by the inclusion of biological testing. None of the material engineers have the necessary competence to carry out biological testing, nor do they have the equipment. This means that the samples have to be transported to another location in another organisation. They come into a queuing system and compete with other tests for other clients. When the samples are tested, it is the biologists who decide how they should be tested and how the results should be interpreted and communicated.

The other partners find this tedious and unsatisfactory. They want more tests, faster tests and lots more information back. They want to optimise many parameters and in order to do this they will need a lot of information and ideally they would like to have the testing going on at the same place as they do the development, and as soon as they have tested the material performance and the distribution of the particles they would like the anti-viral properties to be tested. They would like a rapid feedback loop. They are used to working with situations like this where testing is an important part of the development process, not just a verification of functionality, which is carried out at the end of the development phase. They do not have theoretical models to explain everything they do and they rely on project-specific try and fail methods.

It seems that the biologists are used to a more generic approach where they develop certain standards and methods with should apply in most situations. This does not imply that the material engineers are not working in a structured way, or that they do not have theoretical models; indeed they do. However, as all those working with technology know, the ultimate measure of success is making it work and in this case the theory is incomplete, nobody can actually explain how the nano-particles disable the virus. A great deal of the work done by the material engineers uses theories and methods which have been developed and used before, however to successfully incorporate the new particles in a coating without any loss in anti-viral properties they all use a try and fail method where testing plays a central role. Their own testing is meticulously planned and designed to have a fast turnaround and appropriate feedback. It never occurred to them that the biologists might test in a completely different way.

Recent research on the development of vaccines (Yaqub, 2008, cited in Nelson, 2008) suggests that biological testing of vaccines has developed a particular way of isolating the test environment in order to achieve a high level of accuracy, before any testing on humans; "learning about the efficacy of a possible new vaccine, without jeopardizing safety, can be very difficult, expensive and time consuming" (Nelson 2008:495) Of course in this case it is not a vaccine which is being developed, however SME-Bio are specialists at producing and testing vaccines and the test procedures being used here are based on their tests for the efficacy of flu-vaccines. Procedures based on testing the efficacy of vaccines do not give the flexibility to test, change, test, change the same way as the engineers are used to. The biologists view the testing as a verification process, while to the material engineers it is still a vital part in the development process.

So what does this episode tell us? The two disciplines involved in this project have long histories and have developed their own traditions, their own rules and their own ideas of good and bad practice. It is these culturally evolved fields of practice which make it quite normal for a biologist to test the way he or she does, in fact anything different would be irresponsible perhaps unethical. Standards of approving the tests and the practice of planning, carrying out and documenting the testing are part of his or her training, part of what it is to be a biologist. As such these practices have probably become internalised and would take some conscious effort to explain to others. By working closely over a period of time and developing a kind of "intertwined practice" (Olsen, 2007) participants from different disciplines can learn from each other and create new knowledge. They can also develop the necessary respect for each others expertise which makes the practice of the other discipline acceptable without actually gaining a deep understanding (ibid) The data from this case suggests that some conscious effort has been made by the biologists to make their knowledge explicit, but in order to be fully understood and accepted by the engineers this would probably take a great deal more time, something which a temporary project organisation simply cannot afford.

In order to communicate well, the biologists would have to understand not only how the engineers expect to be informed of test results, but also what the role of testing is, as an embedded part of the material development process. Interpreting and responding to problems embedded in practice is much more challenging than responding to more visible problems (Edwards, 2006:9). This was not immediately obvious to any of the participants. According to theories of socio-cultural learning, we create something new by firstly interpreting something and then responding to it. In order to interpret, we use the resources we have, in this case, disciplinary training and traditional ways of working. These resources then not only shape our interpretation, but also our response. Rather than remaining entrenched in their ways the biologists did eventually reflect upon the issue and this resulted in a new and faster way of testing and the negotiation of new guidelines for reporting test results.

7. Discussion and some conclusions

At the outset of this R&D project it was assumed that the integrated product would require diverse knowledge and skills and the project manager aimed to create an integrated team and to draw upon the knowledge of the various participants. The organisation of the R&D project seems to have functioned quite well as an arena for generating a variety of alternatives, different particles, different coating processes with different particle distributions. However because of time pressures the only way they could complete this project was by working in parallel, denying the participants time to develop trust or to make requirements and ways of working more explicit. Denying them time to develop procedures or rules, which might have eased the interface between the engineering activities and the biological testing. In spite of this they have succeeded in creating new material coatings, which deactivate viruses. All the participants have learned something new from their participation in this project, but apart from the material engineer at University-QM and the biologists who worked together for a period of time, no one felt that they had actually learned much directly from the other discipline.

In spite of the limited learning from each other, the presence of participants from different disciplines has resulted in important and necessary contributions to the development of new anti-viral nanomaterials.

1. The first contribution came before the R&D project actually started and it was in the form of the development of a common object, which subsequently became the goal of the project. (See Figure 4) This common object was an expansion of the original object of the material engineer and of the biologists and may never have evolved in this form without close collaboration.

2. The second contribution was the expansion of the repertoire of material engineers, by adding biological (anti-viral) properties to their existing conceptual models of materials as described in Figure 1.

3. The third contribution is in the form of the change and development of new test procedures more suitable to testing of materials in this type of project (described in 6.3). In this case it was the requirements of one disciplinary group, which initiated the change in the standard practice of the other disciplinary group.

These three examples all exhibit different kinds of interdisciplinary learning. There is a difference in the level of “finding out” going on. If something is known before then it is a case of finding a way of communicating it, finding someone who can translate or an object, which can mediate, as is this case the conceptual model of materials (instance 2). If something is not known as in instance 1, where the anti-viral properties are not known, or in instance 3 where the success factors for the best test results are not known, then it requires a lot more work to develop new solutions. In instance 1 it was resolved by a gradual process extending over a long period of time where participants of the two disciplines worked closely together at the same location. In instance 3 it was resolved by intense discussions with colleagues in the other discipline, followed by reflection on existing practice and eventually the generation of a new faster test procedure.

The participants in this project did not have a common history, which is often so helpful in smoothing the interfaces between different functional groups (Enberg et. al. 2006). This project is typical of many modern technological development projects in its temporary nature and the participants have not had the time to establish relationships of trust or formalise ways of working (Lindkvist, 2005) which might have made it easier to learn from one another. Like the knowledge collectivities described by Lindkvist (ibid), the common goal, in this case of creating a new anti-viral material for use in a future flu epidemic, has pulled all the participants together and given direction to their activities. It is possible that with more time the participants might have made their expectations of each other more explicit and developed formal procedures relating to testing, however in this case the participants were probably not aware of the potential problem. This is similar to observations in academic research (Akkerman et.al. 2006) "Meaning to be generated through diversity requires first that the particularities and the possible boundaries between the group members become actually visible to them" Through discussion the participants in this case *did* eventually became aware of "particularities" (although they did not attribute them to different disciplinary traditions) and were able to develop new solutions.

The lack of a common history is not the same as saying "history doesn't matter". This case demonstrates that history *does* matter and indeed the various histories all exert a great influence on the project by providing the theories and concepts the participants use to interpret and understand and also in the practice with which they are familiar. Looking at the traditions, which have evolved over time in the different disciplines, has helped us to understand why collaboration between the different groups of participants can be problematic. In this case the participants did not blindly follow the rules of their disciplinary backgrounds, as can be seen in the incident of the tensions arising around experimentation, it was their ability to articulate the problems and differences and their ability to adapt existing testing procedures, which allowed them to make progress.

By taking a socio-cultural approach, attention has been drawn to the happenings prior to the project, making it possible to understand the gradual development of the object or the common goal. This approach has also made the links between the disciplinary histories (or voices) of the different participants and their activities more easily visible. A systems view of the project reveals a conflict related to testing, but by taking the multi-voiced view, different nuances appear, which can give a deeper understanding.

This case has provided an example where diverse experts have successfully created an integrated solution. Although tacit foreknowledge from previous projects played a role here, there was little common or shared knowledge. Thus this case provides an example of integration not encompassed by the other perspectives (Table 1). The case has demonstrated several different types of learning taking place, in some cases quite unfamiliar knowledge was easily absorbed from another discipline in other cases the integration of knowledge from the other discipline took time or required negotiation. A deeper understanding of the different ways of learning between disciplines makes it possible to expand the concepts of collaborative knowledge creation to include more diverse disciplines, as in this case, and make the concept more useful for complex modern technological projects and within science-based technologies.

On a more operational level there are implications for organising and managing multidisciplinary R&D projects. An understanding of the some of the different learning mechanisms occurring in multi-disciplinary projects might be a useful tool for R&D project managers. Activities may need to be organised differently depending on how difficult it is for the disciplines to communicate and the depth of understanding necessary to make progress. In this case a lot of the time consuming overlapping work which led to the common object (Figure 4) occurred before the project started, but in some cases this may need to be done within the project. When considering the feasibility of new multidisciplinary projects, it might be pertinent to find out if there are people who have already developed this kind of in-depth understanding and who might act as bridge builders between disciplines. Looking for shared objects to facilitate understanding seems to be rather haphazard and could perhaps become a more systematic technique used in multi-disciplinary projects. Lastly, a greater awareness of the disciplinary differences when trying to resolve conflicts in projects might lead to faster and more reliable solutions. This suggests that managers of multidisciplinary projects, where there is a high element of exploration, should be aware of the variety in the types of learning going on and acknowledge the different requirements in terms of time, proximity and negotiations which may be necessary depending on the circumstances. They should also endeavour to create an environment conducive to interdisciplinary learning and the development of novel solutions.

One aspect of knowledge creation, which has arisen in this case, is the amount of mono-disciplinary learning, which seems to have been taking place in a multi-disciplinary project. A better understanding of how the different disciplines contribute indirectly to each other’s creativity and how the presence of different disciplines in a project affects the overall result might be an interesting area for future research.

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