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What is Nanoscience?' - A Hermeneutic Phenomenological Study of Nanoscience Researchers' Experiences

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‘WHAT IS NANOSCIENCE?’ - A HERMENEUTIC PHENOMENOLOGICAL STUDY OF NANOSCIENCE RESEARCHERS’ EXPERIENCES

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Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy (PhD), is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution.

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Abstract

Nanoscience and nanotechnology have been described as a research area that integrates many scientific and engineering disciplines. However, the integration of disciplines is so complex that the disciplinarity of nanoscience and nanotechnology remains undefined. As a result, the nanoscience and nanotechnology area is viewed as multidisciplinary, or interdisciplinary science, or even as a separate discipline and there is no consensus regarding its disciplinarity. The previous studies conducted in order to describe the disciplinarity associated with this area have focused mainly on political, institutional and external factors while the cognitive aspects of disciplinarity of nanoscience and nanotechnology are still less understood. As a consequence, what is needed from the curricula and training programmes to ensure the growth of this area is not fully understood. When there are strong predictions about the need for an extensive workforce in the nanoscience and nanotechnology area but the disciplinarity associated with it is less understood, it can have an adverse effect on the future of this area. This research fills the gap by aiming to achieve a greater understanding of the nanoscience and nanotechnology area and its associated disciplinarity.

This research focused on examining postgraduate researchers' experiences of nanoscience and nanotechnology research to explore the disciplinarity, knowledge, skills and competences associated with nanoscience research so that a deeper understanding of this area can be achieved.

This research was conducted using hermeneutic interpretive phenomenological methodology to collect and interpret data from twenty five individual semi-structured interviews with postgraduate researchers working in the nanoscience and nanotechnology area. The research methodology was influenced by Max van Manen's ideas of hermeneutic interpretive phenomenology and it was reshaped to best suit the research context and purpose. Examining the researchers' experiences of nanoscience research made it possible to understand how postgraduate researchers perceive, understand and conduct nanoscience research. Further, the examination portrayed what knowledge, skills and competences the postgraduate researchers have applied when working in this area.

The findings from this interpretive study revealed that the postgraduate researchers experienced the nanoscience and nanotechnology area essentially as a 'boundary spanning' experience which described their skills of crossing the disciplinary boundaries in order to understand nanoscience research. Furthermore, the researchers experienced mapping, i.e. their research was evaluated and judged by the researchers from other disciplines. The findings also indicated that the nanoscience and nanotechnology research displayed characteristics of both multidisciplinarity and interdisciplinarity and therefore they suggested that promoting any one particular approach and aiming to develop the researchers for either a multidisciplinary or interdisciplinary platform would not be appropriate for this area. The postgraduate researchers needed the skills to work together with researchers from other disciplines and become good at boundary spanning in the nanoscience area. The interpretive findings were taken back to the postgraduate researchers through a quantitative survey and their agreement with the interpretations further enhanced the credibility of this hermeneutic phenomenological study. The hermeneutic phenomenological research gave a new way to explore the complex nanoscience area by examining the postgraduate researchers' experiences and this research provided an enhanced understanding of the nanoscience and nanotechnology area and its disciplinarity.

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(Note: Portions of this thesis have already been published by the author.)

Chapter 1 Introduction

1.1 The nanoscience and nanotechnology area- changing the dynamics of research and education

In recent times, the nanoscience and nanotechnology[1] area has prominently influenced the research activities in many scientific and engineering disciplines [Schummer 2004]. Nanoscience[2] research has shown ways of developing new materials with different physical, chemical, biological, electrical and mechanical properties at the nanoscale. These properties are not necessarily the same as observed at the macroscale, for instance, carbon in the macroscopic form is non-conducting whereas carbon nanotubes (structure at the nanoscale) can be either semi-conducting or conducting [Crimmel and edits 2013]. These nanoscale properties are therefore referred to as 'novel' as they can lead to new and/or different avenues of applications [Sweeny et al. 2006]. Nanomaterials' applications have spread into many important areas such as medical imaging and diagnostics, electronic and communication engineering, chemical and biotechnology applications, sensors and fuel cell applications and many more [Pandya 2001]. As an immediate response, researchers working in different scientific and engineering disciplines showed a growing interest in studying nanomaterials' development or synthesis, their interactions with other physical, chemical or biological systems and their applications in different research areas [Sweeny et al. 2006]. In parallel, research and development of the nanoscale instruments and techniques have

[1] National Nanotechnology Initiatives (NNI) defines 'nanoscience and nanotechnology' as a research area which deals with the study of phenomena, processes and techniques at nanoscale (1-100 nm) and the applications of nanoscale (1-100 nm) objects. The author follows this definition of 'nanoscience and nanotechnology'.

[2] In this thesis the term 'nanoscience' is used to indicate the collective term 'nanoscience and nanotechnology'.

also captured the attention of scientists, researchers and engineers interested in this area. These instruments and techniques in a real sense enabled the researchers to visualise, manipulate and research on/with these materials at a small scale. In this way, the research and development of such nanoscale instruments and techniques have also become an integral part of nanoscience research [Sweeny et al. 2006]. With promises of new scientific discoveries, nanoscience research impacted on numerous important industries and attracted government and private sector funding [Knol, 2004]. With the increasing research opportunities, growing investments and funding available, nanoscience research has attracted many scientific research institutes, universities and industries. Overall, nanoscience has emerged as a new area of interest for those involved in science, technology and engineering research. Conversely, this emerging research area, due to its complex disciplinary integration has also created new challenges in the education realm; it has raised questions as whether existing degree courses and training programmes in science and engineering disciplines ensure that the students are prepared to be successful researchers in this emerging research field. And if not, what kind of education and training is required in order to thrive in this area. Addressing these questions is important and a first step towards it is can be to understand the very nature of nanoscience research.

Industry and academic experts have supported the idea of addressing the new educational challenges stemming from the rapidly developing nanoscience area through dedicated education research [Roco 2003; Van Horn and Fichtner 2008]. Education experts have expressed the necessity of forward thinking investment in order to develop the necessary workforce for the nanoscience area [National Academic Press 2003; Roco 2003]. Clear predictions about the shortage of a workforce in this area in the near future have been expressed. For example, according to U.S. National Science

Foundation (NSF), more than 2 million jobs will be generated in this area by 2015 [Ernst 2009]. The National Nanotechnology Initiatives (NNI) also expressed a concern about the shortage of a workforce in this area [Roco and Bainbridge 2002]. Similar concerns have been exhibited in other parts of the world [Pandya 2001]. It is argued that there are not many educational opportunities at present to gain the competencies necessary to work in this area [Fonash 2001; Newberry 2012; Wansom 2009]. These reports have suggested that the policy makers in the education area, research institutes, academies and universities should pay attention to this issue which otherwise can impede the growth of nanoscience area due to a lack of an efficient workforce. It is often argued that educational institutes, universities and research centres should take necessary steps to respond to the perceived need in this area. Academic institutes and universities can revisit their existing curricula and training programmes to examine if they are providing the students with an opportunity to learn, develop and practice the necessary knowledge, skills and competences. Further, the institutes and universities should enhance the existing curricula where necessary; or alternatively, develop new curricula and training programmes for the nanoscience area. Such efforts of the appropriate curriculum and training programme development should be backed up with research pursued to understand the very nature of nanoscience. Ever since this area has developed, the scarcity of the awareness of necessary skills and the need to revisit or design new curricula and training programmes in this area has been reported [Fonash 2001; Wansom 2009]. In contrast, the efforts to understand the very nature of nanoscience research which should be equally important have been overlooked.

One approach to develop a greater understanding of nanoscience is by exploring researchers' experiences of working in this area. In this way, an awareness of what challenges these researchers have experienced, and what knowledge, skills and competences they have applied to overcome the challenges successfully can be developed. Such an understanding can support the curriculum development activities in the nanoscience area and ensure the preparation of a future workforce and growth of this area. This thought of exploring the researchers' experiences of the nanoscience area is the base of this research.

1.2 Complexities in disciplinary integration

Nanoscience is described as research which converges or integrates many scientific disciplines [Roco 2003]. However, the integration of different disciplines is so complex to understand that nanoscience remains as an 'unsolved jigsaw puzzle' or 'ill-defined' science [Schummer 2004]. The complexity of integrating the different scientific disciplines leads to the two main challenges in the development of curriculum and training programmes in the nanoscience area. The first challenge is related to the disciplinarity associated with nanoscience and the second is associated with knowledge, skills and competences necessary for such an area that involves a complex disciplinary integration.

Kuhn described four aspects that play a significant role in shaping the disciplinary identity; cognitive, institutional, social and external of a discipline [Kuhn 1970]. Scientific disciplines have readily accepted and represented the discipline with these aspects. Cognitively, a scientific discipline is codified by specifying the vocabulary, methods, techniques, practices, protocol and epistemology in that discipline. The institutional, social and external aspects describe the human resources, institutions, collaborations, infrastructure, research policies and implementations, carrier, communication and networking associated with that discipline [Kuhn 1970]. Both 'multidisciplinarity' and 'interdisciplinarity' in scientific disciplines involve the integration of more than one such scientific discipline. With the complex disciplinary integration of disciplines, there is a range of opinions about the disciplinarity associated with nanoscience. Some referred to nanoscience as 'multidisciplinary' because it uses knowledge and methods of more than one discipline [Battard 2010; Schummer 2004], while some emphasized the 'interdisciplinary' nature of nanoscience arguing that nanoscience research has crossed the cognitive boundaries between the disciplines and has used methods of one discipline into the other [Schummer 2004], others even declared that nanoscience research has emerged as a separate discipline on its own [Poteralska et al. 2007]. In short, there is no consensus regarding the disciplinarity associated with nanoscience.

A number of studies applied bibliometric/scientometric analysis methods to determine the disciplinarity associated with nanoscience. These studies focused on the quantitative information of i) research publications in the inter/cross disciplinary collaborations, ii) citation in the journal papers and patents, iii) research participants, and iv) researchers' profiles. Such studies explored the institutional, social and external aspects related to the disciplinarity of nanoscience research but have tended to neglect the cognitive aspects [Schummer 2004]. The cognitive aspects share different values in the multi and -interdisciplinary areas i.e. the ways in which concepts, terminology, methods, practices and epistemology of disciplines are integrated are not identical in multi and -interdisciplinary platforms. Therefore, cognitive aspects prove to be important in describing the disciplinarity associated with nanoscience [Schummer 2004]. The understanding of the cognitive aspects of nanoscience is also important to inform the teaching and assessment strategies in this area. Based on the facts presented so far, I argue that the cognitive, institutional, social and external aspects are all equally important in defining the disciplinary structure of nanoscience. Therefore, the cognitive aspects associated with the disciplinarity of nanoscience cannot be ignored to visualise a complete picture of the disciplinarity associated with nanoscience research.

Another challenge in the development of curricula and training programmes in the nanoscience is the less researched attributes knowledge, skills and competences [Van Horn and Fichtner 2008]. It has been indicated through research and educational reports that industries largely depend on the educational institutes and the universities for nanoscience workforce development [Pandya 2001; Roco 2002]. They commented that the industries believe that the educational institutes and the universities will reform the curricula and training programmes where necessary to develop a skilled workforce for nanoscience. Although, Stephan et al. discussed that as the nanoscience area is relevantly new, most of the education and training occur informally in the university research laboratories and not through the formal degree programmes dedicated to nanoscience at present [Stephan et al. 2007]. Further, in another qualitative study, Van Horn et al. interviewed the employers in the pharmaceutical and biotechnology industries to examine their perspectives about the skills needed in nanoscience [Van Horn et al. 2009]. They reported that, at present, many employers from these industries have implemented on-site training and they do not have any specific preference for the nanoscience graduates in the hiring process. In such cases, it can be argued that if the nanoscience area grew, and continues to grow without nanoscience undergraduate programmes, are they actually needed. Or, in other words, should we ensure that the necessary knowledge and skills are integrated in the education in core disciplines such that the students can work in the nanoscience area successfully. Although, the future hiring needs were unknown by some of the industries, others have discussed a strong need to develop more interdisciplinary skills and knowledge to thrive in nanoscience area in the future [Abicht et al. 2006; Forfas 2010; Spath 2006]. Also, both of the above studies further mentioned that the informal training in the university laboratories or the on-site industry training could be temporary, as, just like this newer area, the educational approaches for nanoscience also are still emerging. Van Horn et al. [Van Horn and Fichtner 2008] further suggested that the educational institutes and universities should act fast to develop an understanding of nanoscience, and the skills and competences necessary to work in this area in order to support the workforce development. In this context, Malsch argued that the perceived needs of potential employers of nanoscience graduates, engineers and technicians are less reported [Malsch 2008]. Abicht et al. reported a concern about the inadequacy of information on the skills needed for the nanoscience area in the literature [Abicht et al 2006]. They recommended monitoring programmes using a qualitative as well as a quantitative perspective to understand the knowledge, skills and competences necessary for this area.

1.3 Varying trends and perspectives of nanoscience educational programmes

Despite the ambiguity about the disciplinary identity and the limited understanding of knowledge, skills and competences necessary to work in the nanoscience area, there has been an increasing trend of introducing academic courses in nanoscience. These courses are evolved from a wide range of disciplines including the natural and social sciences, and engineering [Fonash 2001; Malsch 2008; Newberry 2012; Poteralska et al. 2007; Powers and Shah 2013]. These are primarily of three types: type A offering a limited supplement of short specialized modules or training course to the existing degree programmes; type B consisting of postgraduate degree programmes; and type C referring to the full nanoscience undergraduate programmes. In a few cases, nanoscience courses have even been introduced/ suggested at K-12 (primary and secondary education) levels [Ernst 2009; Wansom 2009]. According to Malsch [Malsch 2008], the European higher education institutions have focused mainly on the postgraduate programmes. The European Union (EU) funded EuroIndia-Net programme identified 46 nanotechnology research masters courses (in English) in Europe in 2007. Similarly, the European Commission funded Nanoforum Program identified 19 PhD and 78 postgraduate (taught + research based) programmes in nanoscience in Europe in 2005. However, there is also an increasing number of new undergraduate degree courses (type C) in nanoscience, and amongst the three types of programmes mentioned above, the concerns and challenges mainly relate to this type [Brune 2006; Poteralska et al. 2007]. It was also observed that new undergraduate nanoscience programmes or possible reforms in the existing degree programmes have been proposed with wide different perspectives.

Poteralaska et al. discussed that to understand nanoscale phenomena, the students first require good knowledge of the foundations of natural sciences and mathematics [Poteralska et al. 2007]. They argued, the students' disciplinary knowledge of phenomena at a macroscale is still very limited at the undergraduate level, therefore, introducing the nanoscale phenomenon is challenging. Roco discussed that a new generation of researchers, engineers, and technicians, with a deeper understanding of the principles of physics, biology and chemistry as well as good knowledge of the engineering principles of design and processes are necessary for the nanoscience area [Roco 2002]. He emphasized that researchers can make successful contributions in this area if the undergraduate degree programmes in science and engineering disciplines establish an appropriate balance between i) basic disciplinary knowledge and skills and ii) interdisciplinary skills [Roco 2003]. Therefore, instead of developing entirely new nanoscience degree programmes that provide a shallow overview of many disciplines but none in sufficient depth, reforms in the existing curricula by providing the students an interdisciplinary perspective while strengthening the disciplinary expertise are important. Spath et al. argued that an interdisciplinary perspective is a non-negotiable factor in nanoscience education [Spath 2006]. Sweeny et al. examined the feedback of students about their experience of undertaking a nanoscience undergraduate degree programme and reported the importance of increased group activities in laboratories in a nanoscience degree programme [Sweeny et al 2006]. The inclusion of the theories and concepts from the humanities, social science and ethics in nanoscience undergraduate curricula is suggested by many educational experts [Hoover 2009; Powers and Shah 2013; Varma 2000]. Uddin et al. indicated that activities encouraging the students' creative thinking, critical thinking and life-long learning should be enhanced in nanoscience curricula and/or training programmes [Uddin and Raj Chowdhury 2001]. Nanoscience undergraduate degree programme had received a lukewarm support from some experts in this area [Pandya 2001]. Malsch suggested that the specialised knowledge for the multi-disciplinary nanoscience research may only be needed at a late stage in a researcher's career, therefore the undergraduate curricula should focus mainly on the core disciplinary knowledge needed for a foundation in all specialisations [Malsch 2008]. According to Brune et al. nanoscience is so broad and has many disciplines integrated that an interdisciplinary undergraduate education can not only be challenging but even questionable [Brune 2006]. They also commented that in the case of many universities and institutes, the existing undergraduate nanoscience curricula are not very different from the curricula of the corresponding core disciplines. Therefore it is acceptable as the basic disciplinary (science and/or engineering) knowledge. He further argued that sometimes the 'nanoscience' label for undergraduate science or engineering curricula is chosen merely to attract fresh students and increase science and engineering intakes.

All the discussions above provided glimpses of the perspectives associated with the development of nanoscience undergraduate programmes. Based on this, it can be argued that the diverse education community has different perspectives for how to emphasise and deliver the nanoscience undergraduate programmes, or in some cases, whether there is a need of such nanoscience undergraduate courses itself. Although, the information of the contextual knowledge delivered through the existing/ proposed programmes can be obtained, it is equally true that there is no consensus agreement about the structure of such degree programmes; the output of existing programmes, and even about the argument that there is a need for the separate undergraduate nanoscience degree programme. Further, these arguments have remained confined under the labels 'multidisciplinary' and/or 'interdisciplinary' and explained the contextual knowledge. However, how such a perspective (multidisciplinarity/interdisciplinarity) was important in preparing workforce for nanoscience area has not been explained in details. As a result, the confusion about multidisciplinary and interdisciplinary research perspectives in nanoscience research remains in our mind. The root cause of the variations of the espoused claims surrounding the disciplinarity associated with nanoscience needs to be researched.

1.4 Setting the background for research

It is evident from the above discussion that curriculum development in the nanoscience area is not just complex but even questioned sometimes. A main reason behind such varying perceptions which occurred clearly was the ambiguous understanding of the cognitive aspects of disciplinarity associated with nanoscience. The understanding of cognitive aspects of the disciplinarity of nanoscience research is an important foundation stone on which the entire building of curricula and associated pedagogic practices are based [Schummer 2004]. Such an understanding therefore is absolutely essential before justifying the need and type of programmes in the nanoscience area. With the knowledge of cognitive disciplinarity of nanoscience research, one can determine what is needed from education (curricula and training programmes) to ensure the growth of this research area. For instance, if nanoscience is identified as a genuinely multidisciplinary field, a focus will be on reforming the curricula to ensure that the necessary knowledge and skills are integrated in the education in the basic/core disciplines (that nanoscience work is being carried out), and further, to make sure that researchers are competent to face multidisciplinary challenges. While if nanoscience is interdisciplinary, students may need a cognizance to understand different disciplinary perspectives simultaneously and further need to think and communicate critically and reasonably across these disciplinary perspectives. Therefore, if nanoscience turned out as a multidisciplinary science, it may have adverse effects on the future of this area if it is viewed as a separate discipline. In short, there is a pressing need to identify cognitive disciplinarity associated with nanoscience and answer if nanoscience takes up a form of multidisciplinary science, or interdisciplinary science, or a separate discipline or even represent any new form of disciplinarity.

In order to explore the disciplinarity of nanaoscience, the researcher can consider a qualitative, person-centred and holistic perspective and examine how the researchers working in the nanoscience area perceive and understand their research/work, how knowledge is produced and communicated in that area. There have been studied which had indicated a preferred focus on examining researchers' life worlds or practices in laboratories to understand the cognitive aspects associated with the research area

[Latour 1987]. The cognitive domain of interest (disciplinarity) is still very broad and beyond the scope of one single study. This research focused to understand how the researchers working in nanoscience area perceive, understand and conduct their research. From an educator's point of view, such an understanding is valuable knowledge by itself and it is necessary to attain a broader understanding of disciplinarity associated with nanoscience.

Similarly important is the identification of the knowledge, skills and competences necessary to successfully work in this area as these attributes strengthen the students or workforce to face the challenges in nanoscience research area. As perceived by many critics, the need for nanotechnology workers is mainly for postgraduate level researchers at present [Brune 2006]. However, it is also speculated that, in the near future, there will be a huge demand for workforce for the industries and other supporting positions in nanoscience area [Tinker 2006]. According to Hobbs, Head of Research Intel Ireland, the researchers working in the nanoscience area have a direct connection with the industries [EnterpriseIrelandTV archives 2010]. Most of the researchers further pursue their career in the industries; therefore, it will not be wrong to say that they transfer their competences in nanoscience research to the industry setting. Therefore, it can be argued that the knowledge, skills and competences necessary in this area can be best understood at the first place from the researchers who presently working in this area.

1.5 Research questions

It is now clear that the cognitive aspects of disciplinarity associated with nanoscience are less understood to date. Further, there is scarcity of knowledge about the attributes, knowledge, skills and competences necessary to work in this area. This led to the two questions which need to be discussed to answer my main question ‘What is nanoscience?’

- **How can the disciplinarity associated with nanoscience be defined?**
- **What core knowledge, skills and competences are necessary to successfully research in the nanoscience area?**

As indicated earlier, I aim to address these research questions from postgraduate researchers’ perceptions and understanding of their research in nanoscience research area. There were different possible ways to approach postgraduate researchers’ ideas, perceptions and understanding about nanoscience research. These included surveys, polls, focus groups or interviews. With quantitative surveys and polls, there was a danger that this inquiry of perceptions and understanding would be confined to pre-determined words. In that sense, focus groups could be preferred over surveys. However, considering the broad spectrum of the postgraduate researchers working in many different research areas in nanoscience, focus groups would have been unlikely to collect all knowledge about how the individual postgraduate researchers’ perceive this research area and understand their research in the nanoscience area. Interviews were a good resource for exploring postgraduate researchers’ perceptions and understanding, considering that they were definitely beyond asking the same questions to each researcher in similar ways and just getting their opinions [Bailey 1996]. There needed a deeper insight into the individual researchers’ lives, in other words, a portrayal of their experiences or life worlds. These experiences can bring to the forefront the researchers’ perceptions and understanding of nanoscience research. Postgraduate researchers’ experiences (or lived reality or life worlds) thereby were central in this research and the focus was on examining their experiences of nanoscience research. The examination of the researchers' experiences of nanoscience research can reveal the truth (or the reality) of how they perceive and understand nanoscience research and provides an insider's perspective to understand the very nature of nanoscience research and its associated disciplinarity. Such understanding is drawn from the researchers themselves and is not based on any facts, prejudices or presuppositions.

Having identified my particular interest in examining the postgraduate researchers' experiences of 'researching in the nanoscience area', the central phenomenological question of this research is:

- **How do postgraduate researchers' experience the phenomenon of 'researching in the nanoscience area'?**

Grounding phenomenology in the interpretivist tradition was well suited for this qualitative inquiry as the phenomenological study aims to understand the lived experiences of the individuals [Laverty 2003]. Further, from the start, there were no prejudices that there could be limited ways in which postgraduate researchers experience nanoscience research. The foundation of phenomenology is that 'reality can be multiple' and those can be examined by studying the human experiences' [Laverty 2003]. Postgraduate researchers describe their lived experiences through events and stories and thus portray the phenomenon of 'researching in the nanoscience area' as they have experienced. These events and stories can be different for each participant. These events and stories, and thereby, their lived experiences can be examined to understand the phenomenon of 'researching in the nanoscience area' newly from the participants themselves. Therefore, it can be argued that the phenomenological examination of researchers' experiences has much to offer to the newer and broader understanding of nanoscience research.

In this thesis I proposed to research the postgraduate researchers' experiences of the nanoscience area through a phenomenological examination in order to address the two questions discussed above which in turn answered the main question 'What is nanoscience?' as posed in the thesis title. Philosophical notions of Heidegger and Gadamer on hermeneutic phenomenology [Finley 2009; Giles 2008] and van Manen's ideas of hermeneutic interpretive phenomenology [van Manen 1997] underpinned this qualitative research.

1.6 Summary

This chapter set the context of this research, explained the focus of the study and introduced the two research questions to answer the main question 'What is nanoscience?' The focus of this research was set on examining the postgraduate researchers' experiences of nanoscience research to attain a deeper understanding of the nanoscience area. The examination of researchers' experiences also gives an insight into what knowledge, skills and competences the postgraduate researchers applied to work in the nanoscience area.

The thesis is organized in seven chapters. An outline of the organisation of the chapters is given below.

1.7 Structure of the thesis

Chapter 1- Introduction

In chapter 1, the background of the study, research questions and the statement of the phenomenological research question are introduced.

Chapter 2 - Literature review

Based on the background of the study discussed in chapter 1, chapter 2 contains a detailed review of the current literature on the related aspects. The terms and concepts associated with this research such as disciplinarity, multi and inter-disciplinarity, knowledge, skills and competences are discussed in this chapter. A literature review of prior studies associated with the disciplinarity, and the attributes knowledge, skills and competences of nanoscience research is presented.

Chapter 3 - Research methodology- philosophical foundation

Chapter 3 and chapter 4 describe the particular approach taken in this study to address the research questions. In chapter 3, the knowledge claims and theoretical perspectives adopted in this research are discussed. The philosophies of Van Manen, Gadamer and Heidegger which influenced this research are discussed in chapter 3. It is followed by a description of the methodological (hermeneutic interpretive phenomenology) choices made in the research.

Chapter 4 - Research method in action

In chapter 4, information of the research participants and the ethical considerations are discussed. A comprehensive explanation of the specific method of data collection and data analysis process is provided. Further, I discuss the measures taken in order to ensure the trustworthiness and rigour of the research in the study in the form of decision trails. An example of a crafted story is included in this chapter.

Chapter 5 - Research data analysis

Chapter 5 and chapter 6 together present the interpretive analysis of the research data. Chapter 5 in section 5.2 discusses an example of hermeneutic interpretive phenomenological analysis of an individual transcript. Section 5.3 discusses the holistic themes and interpretive analysis of all the crafted stories considered as a group.

Chapter 6 - Understanding newly the phenomenon of 'researching in the nanoscience area'

Chapter 6 draws together the ideas from chapter 5 and discusses the essential themes derived from the interpretive analysis in this chapter. The essential themes and interpretive explanation offer a more holistic understanding of how the phenomenon of 'researching in the nanoscience area' was experienced by postgraduate researchers. The newer understanding of the phenomenon is an epilogue of the hermeneutic phenomenological examination.

Chapter 7 - Discussion and conclusions

Chapter 7 describes the new understanding of the nanoscience area gained from the hermeneutic interpretive phenomenological research. It discusses the guidelines and recommendations for the curriculum development in this area. Further, the details of the quantitative survey constructed on the basis of the findings of the phenomenological examination are discussed in this chapter.

Chapter 7 further summarises the overall research findings and includes the concluding thoughts about the research and the recommendations for future work.

Chapter 2 Literature review

2.1 Introduction

In this thesis the postgraduate researchers' experiences of nanoscience area are examined in a hermeneutic phenomenological framework. The postgraduate researchers' experiences portray a picture of how the researchers perceive and understand nanoscience research, giving an insider's perspectives. The examination of their experiences thereby provides a newer understanding of the phenomenon of 'researching in the nanoscience area'.

Previous understanding of the contextual knowledge and theories related to the research interest is important in any investigation. From the notions of hermeneutic phenomenology suggested by van Manen, a researcher can approach the phenomenon of interest without bracketing the known understanding about it. However in the process, he/she should be aware of his/her prejudices and equally remain open to incorporate and assimilate any newer meanings emerging from the analysis [Giles 2008; van Manen 1997]. These notions complemented the importance of literature review before approaching the phenomenon of interest. In this chapter, I discuss the terms/theories associated with this research and review the existing research in this area.

2.2 Concept of scientific discipline, multi and inter-disciplinarity of scientific disciplines

In this section I describe the notions of scientific discipline, multidisciplinarity and interdisciplinarity.

2.2.1 Notion of discipline

The term 'discipline' derived from word 'disciplina' has its origin in Latin word *discere,* meaning teaching [Krishnan 2009; Stichweh 2003]. In the early eighteenth century, the word 'disciplina' together with the word '*doctrina',* meaning intellectual, was used to refer to the pedagogical methods of teaching and learning knowledge. The word *'discipulus'* meaning pupil, in conjunction with the word *'discere'* was more often used to describe learning by pupil. Later, the discipline was recognized as a system of storing the archived knowledge of particular realms [Stichweh 2003]. The discipline became evident as 'a producer of new knowledge' when people with an interest in specific realms, started concentrating on parts of the knowledge of that realm to advance it further. Such movement resulted in the development of different roles (or positions) dedicated to that disciplinary knowledge, promoted by people who dedicated their interest and work in pursuit of that particular knowledge. On a larger scale, such movement resulted in emergence of the scientific disciplines with the specific knowledge institutionalized as a tradition, an institute, a kingdom or a hallmark of the disciplines [Stichweh 2003]. Different roles (or positions) were later associated with the occupations that were based on the values (or traditions) of that discipline. Members of that discipline represented a community of that discipline.

Kuhn theorized the emergence of scientific disciplines and scientific communities as synonymous events. Scientific communities are specialist or experts of the scientific disciplines who evaluated the body of knowledge of that discipline and classified (or categorised) the discipline from others, by means of shared values, interactions with other experts (with similar interests) and experience. Scientific communities fixed the ways of communicating the knowledge of that discipline. The most modern form of scientific communication is the scientific journal. Several paradigms were finalised by the experts of disciplines to decide the scope (spread, extent or territory) of the disciplinary knowledge. Any new knowledge when considered to be added to that discipline was certified on the basis of ‘consensuses’ of the experts of that discipline. Scientific disciplines therefore are creations of humans and characterised by particular knowledge bases, expertise, specific methods, vocabulary and interests. Horne argued that, profoundly, the disciplines are nothing but shared ‘ego’ by a group of experts [Newberry 2012].

Research in any scientific discipline is about understanding the knowledge and making efforts to test the new knowledge to be introduced in that discipline, while strictly maintaining the discipline specific rigour of inquiry [Krishnan 2009]. Researchers are further bound to communicate the knowledge as per the practices of that discipline. More recently, Shneider described four stages of the evolution of a scientific discipline and what researchers particularly aim to achieve in that stage [Shneider 2009].

- First stage - Introduction of new objects, phenomena and a language to explain these objects and/or phenomena

- Second stage- Development of tools, techniques, protocols and methods for the new discipline and acquiring further knowledge of the objects and phenomena.

- Third stage- Approaching the objects and phenomena with the tools developed in the earlier stage and creating new insights, answers and questions.

- Fourth stage- Carry forward the knowledge generated in the previous stages and continuously evaluate the disciplinary position.

Shneider argued that the skills needed to undertake research at each of these evolutionary stages may not necessarily overlap as the researchers' aims, interests and mind-sets could be different in each of this stage. However, he also commented that a mix of researchers with abilities to work in these different evolutionary stages can be instrumental for the overall success of research in that discipline [Shneider 2009].

Biglin, in 1973, suggested three dimensions of classifying disciplines [Gorsky et al. 2010]. These dimensions are 'hard or soft'; 'pure or applied' and 'life or non-life'. The 'hard or soft' dimension is related to the degree to which the paradigms exist, the instructional strategies being different in each dimension. 'Hard' was characterized as objective whereas 'soft' as subjective or relative. To demonstrate, natural sciences would fit in the hard category and social science in the soft. The 'pure or applied' dimension was based on the degree of concern of the application. For instance, mathematics is considered as a pure (or theoretical) discipline, on the other hand, engineering as applied discipline. The 'living or non-living' dimension related to the degree of concern with the living system [Gorsky et al. 2010]. Biglin suggested the categorisation of disciplines, while also acknowledging the possibility of straddling the boundaries of disciplines [Gorsky et al. 2010]. Van den Daele and Weingart, in 1976, discussed three aspects that play a major role in the formation of a scientific discipline as well as differentiating it from other scientific disciplines [Kuruth and Maseen 2006]. These aspects are cognitive, institutional and social (also referred to as political or external in some papers). Cognitive aspects specify how knowledge is produced in that discipline. These aspects involve the epistemic practises such as the students' activities to develop their understanding and/or instructional strategies associated with that discipline. Further, these aspects also include the key words or vocabulary to name/explain something in that discipline. Horne referred to such discipline specific vocabulary as 'jargon' as the knowledge of that discipline remains restricted or confined to that discipline [Newberry 2012]. Other studies have argued that cognitive aspects have constrained the knowledge creation on the platform of multiple disciplines [Stichweh 2009; Latour 1987; Newberry 2012]. In the institutional aspects, a scientific discipline is considered as a social system therefore emphasis is given to processes such as communication, interpersonal relationships, career, profile, professional practice and networking. Social aspects consider how a scientific discipline is influenced, driven or controlled by social/ political or external factors. Horne had commented that the disciplinary boundaries are relative as a discipline itself is defined by the experts relatively i.e. the knowledge of one discipline is agreed by its non-suitability in other discipline. He therefore argued that the boundaries of the disciplines are human generated, rigid and complex. Although, it is also argued that there is a possibility of transgression if necessary [Newberry 2012].

2.2.2 Notions of multidisciplinarity and interdisciplinarity

It is argued that when scientific disciplines face complex challenges, the experts from one or more disciplines may need to step in and contribute together to face these challenges [Krishnan 2009; Repko 2006]. Repko discussed that such complex challenges sometimes necessitated the transgression or 'loosening up' of disciplines. However, the transgression of disciplines was more complex than imagined and faced practical challenges. For instance, Krishnan discussed the challenges when the problems/solutions are communicated across the disciplines and commented that the problems/solutions communicated across disciplines can have a few forms i) as communicated by the original/first discipline, ii) as understood and approached by other discipline and iii) as reverted and understood by the original discipline [Krishnan

2009]. Similarly, Gibbons et al. explained the notion of technological evolution and explained how it influenced the convergence of scientific disciplines as the researchers from any one scientific discipline cannot solely control or predict the path technology can lead to [Gibbons et al. 1994]. Further, the technological evolution was not just limited to scientific disciplines but included social and ethical domains as the technology many a times are directly related with public domain in the form of promises and visions. For instance, the nanotechnology research area exhibited potential of many promising applications of nanoscale particles in textile, medical and healthcare industries but at the same time how nanoparticles affect human life span or environment was questioned. Gibbons et al. argued that such technological evolution therefore not only necessitated researchers from many diverge disciplines to work together in the knowledge production but it brought science, technology and society together, and thereby, added increased social and ethical responsibilities on the researchers working in this area [Gibbons et al. 1994]. As a result, the convergence due to technological evolution has been more complex.

Both ‘multidisciplinarity’ and ‘interdisciplinarity’ originated as a notion of transgression resulting in the interaction of two or more scientific disciplines. Multidisciplinarity and interdisciplinarity both refer to the involvement or convergence of two or more disciplines. However, there are basic differences between these two types of activity. In multidisciplinary research, the research objective is approached from different angles using different disciplinary perspectives but these perspectives are not necessarily integrated. In other words, multidisciplinary research draws on the knowledge and theories from different disciplines but stays within their boundaries, viewing one discipline from the perspective of another. The integration of knowledge in multidisciplinary research can happen in a narrow context. For example, a computer engineer, expert in writing codes can develop a computer code (program) when mathematical formulas are provided to him. The program can be applied to analyse biomedical data by a medical researcher. In interdisciplinary research, different disciplines are integrated in such a way that the overlap can create its own theoretical, conceptual and methodological identity [Besselaar and Heimeriks 2001]. In the report ‘Facilitating interdisciplinary research’ the National Academy of Sciences (NAS), the National Academy of Engineering (NAE) and National Academics (NA) have defined interdisciplinary research as ‘A mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or the area of research practice’[National Academic Press 2004]. Although, multidisciplinarity is welcomed within the scientific disciplines, there exist mixed views about interdisciplinarity. Fish referred to interdisciplinarity as an attack on disciplinary boundaries which is bound to fail politically as well as cognitively [Fish 1989]. He argued that the disciplinary boundaries strictly guard inquiry and legitimize the new knowledge in that discipline. Transgression of the boundaries may result only in new divisions and new authorities. Repko on the other hand, has argued that interdisciplinary research strengthen the core disciplines rather than weakening them [Repko 2006]. However, he also emphasized that it is equally challenging for the associated pedagogic practices to balance the time devoted for developing an adequacy in the relevant discipline as well as the time needed to develop an interdisciplinary understanding. There are positive predictions about the future of multidisciplinary and/or interdisciplinary sciences, with researchers expecting breakthrough discoveries when the different scientific disciplines collaborate in an interdisciplinary or multidisciplinary network [Rafols and Meyer 2007; Youngblood 2007]. Youngblood discussed that interdisciplinarity research should be viewed as a process of bridging the scientific disciplines, in order to solve the complex problems instead of claiming it as an academic discipline [Youngblood 2007]. Higher education institutes should restructure their curricula, collaboration and facilities in order to facilitate such research. Similarly, there are studies which have reported that the disciplinary integration although brought researchers from different disciplines together, they knowledge and attitudes are not integrated/matched easily and there exists disciplinary boundaries and hegemonies of disciplines and researchers work at the boundaries of the scientific disciplines [Latour 1987]. Gibbons et al. and Nowtony et al. further discussed the work at disciplinary boundaries as problem driven research where researchers continuously effort to transcend knowledge in relation to the specific research problems. Therefore, they argued that both interdisciplinarity and multidisciplinarity can also be described as trans- disciplinary research where the disciplinary boundaries are less and less relevant [Gibbons 1994; Nowotny 2001]. Overall, there are mixed views about multidisciplinarity, interdisciplinarity and of disciplinary integration. As the debate continues, I focus on the narrowed spectrum of nanoscience research and associated disciplinarity.

2.3 Nanoscience research – associated disciplinarity review

This section summarises the different views of researchers, scientists and education researchers on the disciplinarity associated with nanoscience research. This literature review was conducted with a focus on understanding the different notations and/or descriptions used to explain the disciplinarity associated with this research area in research papers and educational reports available to date. Although there is a vast body of literature which introduced nanoscience research as a 'multidisciplinary', or 'interdisciplinary', or as a newly emerging 'separate' discipline, these terms indicated the complex disciplinary integration. Such literature has a primary focus on scientific research and the terms used to define nanoscience research need not necessarily explain the specific views attached with such a description of disciplinarity. Therefore, it was important to review specific literature which explained the disciplinary views associated with nanoscience research.

Schummer contributed to the investigation of the disciplinarity of nanoscience research by carrying out scientometric investigations [Schummer 2004]. He argued that nanoscience research as a whole is neither particularly multidisciplinary nor interdisciplinary. The research area includes 'nano-chemistry' or chemistry at nanoscale; 'nano-physics' or physics at nanoscale; and 'nano-electrical engineering' or electrical engineering at nanoscale. He attributed these areas as 'subsections' of the independent or core disciplines which described the knowledge at nanoscale. Therefore, these subsections collaborate exactly as the traditional disciplines do, when the disciplinary identity of science 'as a whole' is discussed. As a result, the multidisciplinarity of nanoscience research stood as trivial as the case of whole science and engineering in general. He suggested two patterns that could fit to nanoscience research in relation to its interdisciplinarity. In the first pattern, several auxiliary disciplines are strongly associated with a major (or mother) discipline, with the researchers working in auxiliary disciplines contributing to the major (or mother) discipline. He argued that, such a pattern continues to accept boundaries between the scientific disciplines and limits the infrastructure such as research institutes, curricula, research journals and career opportunities to the major discipline. Nanoscience research following this pattern represents a cluster of auxiliary disciplines deeply integrated with the major disciplines, where the major disciplines continue to dominate. Nanoscience research does not differ greatly in terms of the institutional aspects of major disciplines including collaboration, communication, scientific journals and networking. In the second pattern, many different major disciplines had strong connections (or ties) to each other. This pattern, in contrast with the first, would require reorganising a new research landscape around nanoscience for interdisciplinary research. Such an effort would involve overcoming the cognitive barriers and cultivating a new, independent social infrastructure for interdisciplinary nanoscience research.

Thinking of cognitive barriers in interdisciplinary nanoscience research, it is important to understand first where the different major disciplines meet within this research area. Two common links between different disciplines involved in nanoscience research have been discussed to date. The first is 'nanoscale objects' and 'nanoscale instruments' is the second [Battard 2010; Kaplan 2012]. Although, there exists a fundamental vagueness about what is included under nanoscale and how we define nanoscience itself, I prefer to continue with the definition of nanoscience discussed by NNI (National Nanotechnology Initiatives) in this thesis to avoid entering into another new debate and getting defocused from the disciplinarity issue. Therefore, we refer to objects with at least one of the dimensions between 1-100 nm as 'nanoscale' objects.

Schummer argued that researchers sharing common nanoscale objects may have different understanding of such 'shared object' within each discipline [Schummer 2004]. For instance, if we consider gold nanoparticles, the physicists may be familiar with its size and spatial structure; chemists may be interested in solubility, catalytic properties and dynamics; engineers may be aware of the electrical properties and biologists may be familiar with the biological functionality and may be interested in its biological applications such as carriers for drugs and gene delivery. Although they all are sharing a common nano-scale object, each discipline had perceived it differently for diverse applications. Experts in physics and chemistry can argue that the alteration of size, and thereby the surface, could change electrical, mechanical or catalytic properties; therefore the properties of the objects in different disciplines can be interlinked. However, it is important to note that the researchers' understanding of the object matter in each discipline itself is different. Therefore, what is discussed as a 'shared object' in nanoscience research is perceived differently in each discipline. In other words, 'shared object' is understood separately in the cognitive domain of each discipline. When such disciplines are brought together in nanoscience research, the researchers may not perceive the connections between the disciplines easily. Rafols and Meyer in this context argued that researchers have to put extra efforts into articulating their knowledge when such diverse knowledge bodies are brought on a common platform [Rafols and Meyer 2007]. Therefore, nanoscale objects serving as 'shared objects' across multiple disciplines in nanoscience research may not be understood similarly by all disciplines, however it surely impacts the disciplinarity identity of nanoscience research.

Another common link of the disciplines in nanoscience research is 'nanoscale instruments'. Kaplan et al. described nanoscale instruments as a common ground for researchers from many disciplines [Kaplan 2012]. However, they also reported that the interpretation of results was considered as a big challenge for researchers from different disciplines working on a common nanoscale instrument as they approach it with different knowledge and perspectives. For example, a biologist using atomic force microscopy may be interested in identifying biomarkers in the cell at nanoscale, while a physicist with the same samples and nanoscale instruments are interested in understanding the mechanics of the cell by studying acoustic and elastic properties, although both types of research are aimed at identifying tumorous cells in the sample.

The ‘technological paradigms’ are also referred to as another cognitive barrier in the interdisciplinarity of nanoscience research [Sweeny, Vaidyanathan and Seal 2006]. The technological paradigms are deeply rooted within the scientific discipline and are formulated on the previous successful attempts in the research of that discipline. In order to solve complex problems, it is well understood now that disciplines integrate. Under the technological vision, the technological paradigms of one discipline can be applied to solve issues in the other disciplines. However, in the process, the technological paradigms often encounter the paradigms guided by the opposite view (of the other discipline). For example, Schummer has explained that technological paradigms in mechanical engineering have resulted in development of new, high end and precise instrumentation. This instrumentation in turn has facilitated the control of atomic and molecular level assembly. Such instrumentation therefore has exhibited a potential of developing new chemical compositions of nanoscale under artificial and/or controlled environment. However, such ‘artificial or controlled’ development of nanoscale chemical compositions has challenged the technological paradigm of the chemistry discipline which is deeply embedded around the concept of ‘self-assembly’ [Schummer 2004]. Sweeny et al. described the ‘bottom-up’ and ‘top-down’ approach in a similar context [Sweeny et al. 2006]. Both the bottom-up and top-down approaches are related to the manufacturing of nanomaterials. The ‘bottom-up’ approach deals with the engineering specific molecules and substrate interactions from bottom to the top to achieve a desired dimension or assembly. While the ‘top-down’ approach deals with achieving a finite structure by reducing the existing material until desired dimensions are achieved. Although nanoscience brings together these two research approaches (controlled development and self-assembly; or top-down and bottom-up) guided by the two very opposing views, how they can be merged in the (paradigms of) interdisciplinarity of nanoscience research is less understood to date.

Examining the institutional and external aspects through scientometric studies, Schummer reported that the research infrastructure, research papers and networking between the disciplines in the nanoscience research area has been undergoing dynamic changes in recent times [Schummer 2004]. In this way, social sciences, ethics and humanities are also becoming an integral part of nanoscience research [Associates 2006]. Schummer argued that these dynamic changes in institutional and political aspects associated with nanoscience research have reflected a growing inclination of the research community towards the second pattern of interdisciplinarity involving complex but strong ties between major disciplines. Such interdisciplinarity however is less understood by the research community to date. With the growing interest of researchers to integrate major disciplines, Schummer also commented that the research community is trying to portray the future of nanoscience as a 'complex super-interdisciplinary structure' that merges the whole of science, social sciences and the humanities together. However, he emphasizes that success of such a complex structure will require critical understanding of the interdisciplinarity of nanoscience.

Roco and Bainbridge proposed the term 'convergence' of the disciplines to explain connections between the different scientific disciplines contributing in nanoscience research [Roco and Bainbridge 2002]. They argued that nanoscience has been multidisciplinary already for many years and the interdisciplinary connections between different scientific disciplines need to be promoted at this time. Roco envisioned 'a learning pyramid' for the undergraduate education developed with an interdisciplinary perspective [Roco 2003]. The pyramid started with the specific techniques taught in the first year, followed by gradual introduction of its potential in different disciplines at the higher levels leading to a coherent understanding of physical; chemical and biological features as the output of the learning pyramid [Roco 2003]. He further emphasized the reorganisation of the entire research framework around the nanoscience area with a more interdisciplinary perspective. For accomplishing the interdisciplinary vision of nanoscience, Roco discussed the necessity of identifying the factors constraining as well as promoting the interdisciplinarity in nanoscience [Roco 2003]. In the same context, Porter et al. described 'the difficulty in locating relevant research in other disciplinary contexts' as one of the challenges faced by the researchers in this research area [Porter and Youtie 2009]. Roco further argued that researchers working in the nanoscience area are taught often in the core or major disciplines [Roco 2003]. As a result, they understand the connections between different disciplines only in the later stage of their PhDs (postgraduate research). If this is the case, then, an examination of postgraduate researchers' experiences of nanoscience research can provide knowledge of how the disciplinary connections are understood by the postgraduate researchers. Such an understanding is required for determining skills necessary for the workforce in this area and to inform education policy.

In another study, Sweeny et al. explained that the convergence of nanoscience research with disciplines such as biotechnology, information technology and engineering promises tremendous growth of this research area [Sweeny et al. 2006]. However, such a convergence inevitably should be accompanied by the awareness of emerging social and ethical issues amongst researchers, professionals, students and the public. They have emphasized that the convergence has brought social science and ethics closer to this research area. As a result, teaching and research organizations are advised to reconstruct the instructional guidelines to include social and ethical issues in science.

Porter et al. [Porter and Youtie 2009] reviewed the interdisciplinarity of nanoscience research with a scientometric analysis method. The scientometric method aims at a quantitative evaluation of relationship between peoples, group of people or science phenomena with each other based on the bibliometric or citation data. In their study, Porter et al. focused on different research areas included within nanoscience research and the citations in the research papers published in these areas. They reported a dominance or prime linkage of material science with many major disciplines including physics, chemistry, and electrical engineering within nanoscience research. They further discussed that material science research was also related with the disciplines including clinical medicine, mathematics and biomedical science. The study suggested that within nanoscience research, many major disciplines cluster around materials sciences and the knowledge exchange takes place in material science research. Similar observations were reported by Battard in the case of material science and molecular biology [Battard 2010]. He referred to material science and molecular biology disciplines as 'crossroads' where the boundaries between different scientific disciplines meet in the nanoscience research area, the two disciplines being major disciplines in nanoscience research. Porter et al. further commented that the 'interdisciplinarity' factor in quantitative results of the bibliometric studies was high only as a virtue of researchers' tendencies to cite work in the neighbouring disciplines [Porter and Youtie 2009]. Eto carried out a bibliometric analysis of research journals, citations and authorship patterns to analyse the disciplinary factor in the case of Japanese government sponsored nanoscience projects [Eto 2003]. He suggested that the multidisciplinarity in nanoscience research has the chemistry discipline at the central position. The multidisciplinarity has been extending to physics and material sciences and, to a lesser extent to biology and engineering.

Many of the studies described earlier have expressed concerns about the cognitive barriers arising with the interdisciplinarity and/or multidisciplinarity of nanoscience research. However, a small body of literature also indicated the possibilities of successful migration of concepts within different disciplines in nanoscience research. Grodal and Thoma, through a patent analysis method, reported that the biotechnology research area and the nanoscience area have allowed the migration or 'cross-pollination' of a few technological concepts [Grodal and Thoma 2008]. They argued that such migration of technological concepts has given rise to a new research area called 'nano-biotechnology' within nanoscience research. Similarly, Battard reported a cross-pollination or migration of concepts within the disciplines is possible at nanoscience research laboratories as a virtue of shared nanoscale instruments [Battard 2010]. Through a qualitative study, he reported that nanoscience research represents a strong multidisciplinary research framework. He argued that the research collaborations within many disciplines working in this area have been possible by mutual trust and legitimacy of scientific instruments. Further, he also commented that in order to achieve the cross-pollination, researchers from different disciplines have to make some adaptation in terms of vocabulary while working at the nanoscale instruments. For example, that researchers can share the experimental details with simplified terms which otherwise are taken-for-granted in a discussion between researchers of the same discipline [Battard 2010]. The research was based on case studies with the postgraduate and postdoctoral researchers working in a nanoscience research laboratory as the research participants.

2.4 Reorganising disciplinary identity of disciplines involved in nanoscience research

Many scientific disciplines under nanoscience research have focused on investigating the theories, phenomena, materials and tools applicable at nanoscale. To include the newer knowledge produced as a result of these investigations, the scientific disciplines have reformed their disciplinary boundaries and such reformations have affected the disciplinary identity of the nanoscience area. Porter et al, as discussed earlier, reviewed the disciplinary reformations in the case of physics and chemistry disciplines in the nanoscience research area. He discussed that both these major disciplines share strong ties with material science research in nanoscience area [Porter and Youtie 2009]. Similarly, Kuruth et al. discussed how the entry of toxicology into nanoscience research has reformed the disciplinary identity of toxicology [Kuruth and Maseen 2006]. This study applied a qualitative research approach to investigate how the reformation of disciplinary identity of toxicology affected the disciplinarity of nanoscience research. As my research is also aimed at examining postgraduate researchers' experiences in a qualitative framework, the above study was of particular interest to me.

The toxicology discipline is dedicated to the examination of potentially harmful effects of chemical, or physical agents, on biological systems and environment [Oberdorster 2005]. Kuruth et al. conducted qualitative interviews with particle toxicologists working in the nanoscience area in order to collect their views of reformation of disciplinary identity of toxicology in the nanoscience area. Particle toxicologists examine the toxicity of nano-particles for different biological systems. Kuruth et al. reported that the toxicology discipline entering to nanoscience research had taken a definitive role in the formation of cognitive, institutional and social framing of nanoscience [Kuruth and Maseen 2006]. They discussed that toxicology brought much of its well established knowledge and practices to nanoscience research. Many practices and techniques involved in studying health effects of particles of typically micro (10^{-6}m) dimensions were applied for similar examinations of nanoscale particles, and equivalently, it provided room for the new research to analyse the potential impacts of newly engineered nanoscale particles.

In relation to the institutional aspects, funding applications in toxicology research area have seen an inclination to include the word ‘nano’ in comparison with ‘micro’ considering a greater chance of success in securing funding with this ‘buzz’ word [Oberdorster 2005]. Further, with the increasing growth of nanoscience research, in many scientific disciplines the demand for toxicology for risk assessment is increasing. Many scientific research groups introduced toxicology research groups within their research cluster. As a result the professional role, career opportunities and networking in the toxicology discipline have been influenced by nanoscience research [Oberdorster 2005; Kuruth and Maseen 2006].

Toxicology research in the nanoscience area has also seen some changes in relation to the social or external aspects. Toxicology research has benefited society by constructing a new knowledge base to inform the society of the potential hazards of different physical or chemical agents (such as industrial ultrafine particles, nanoscale particles). However, the toxicology research community are viewed as the ‘bearers of the bad news’ as the positive or favourable result in toxicology are associated with the hazard due to the physical or chemical agent under review. The toxicology research community prefer to be referred to as a ‘productive partner’ than ‘critic’ which was achievable to a certain extent through ties with the nanoscience research. Part of the toxicology research in nanoscience area has oriented the knowledge base towards other auxiliary disciplines such as therapeutic science, where the same knowledge base of toxicology has been used for the production of nano scale particles for health applications.

In section 2.2 and 2.3 of the thesis, the existing literature about the disciplinarity of nanoscience is discussed. It is clear that the researchers, educational experts, industries and policy makers do not agree to a unique answer about the disciplinarity of nanoscience research. Also, it is clear that the disciplinarity of nanoscience is particularly complex when one considers the cognitive aspects associated with it. In spite of indications of the complexity of the problem, one may think what difference will it make if nanoscience research is referred to as ‘multidisciplinary’, or ‘interdisciplinary’, or a ‘unique discipline’ or something else. I would argue that if the labels are for attracting new students in the science and engineering discipline, or for increasing research funding opportunities, it may not. However, the cognitive aspects of the disciplinarity of nanoscience research should be clearly understood as these must inform curriculum development in this area, as each of these labels have different perspectives of integrating scientific disciplines.

2.5 Knowledge, skills and competences: associated typologies

The second question of interest in the thesis is related to the knowledge, skills and competences necessary to work in nanoscience area. A vast body of literature has described these attributes and there are many educational reports describing the methods to examine the development of these attributes [Anderson 1982; Proctor and Dutta 1995; Winterton et al. 2006; Zoller and Pushkin 2007].

2.5.1 Skill

The term 'skill' in general refers to the ability of using knowledge and applying it in a particular context. It is a measure of the level of performance in the sense of accuracy and speed in carrying out a particular task/process. Winterton et al. reviewed the typologies related to 'skill' and first cited work of Pear describing the term 'skill' as an attribute limited to manual activities [Winterton et al. 2006]. They further cited Welford's work who broadened the definition of 'skill' by including the mental/cognitive activities with manual activities [Winterton et al. 2006]. Welford suggested that the cognitive activities establish a connection between the perceptions and the manual activities generated as a response to it. Proctor and Dutta have defined a skill as 'goal-directed and well organised behaviour, acquired through practice, and performed with the economy of effort' [Proctor and Dutta 1995].

Fitts discussed a three stage process to explain the process of skill acquisition in a classroom context [Fitts 1964]. The first stage involved the cognitive processes by which the nature of the task and how it should be performed is understood by the individual. Since this stage is dedicated to the understanding of the task, the performance of the individual at this stage can be slower and inaccurate. The second stage has been referred to as the associative phase. In this phase, the inputs are linked more directly to the appropriate actions, errors are detected and eliminated, and thereby, proficiency in the activity is increased. The last stage is the autonomous phase where the performance reaches to a level where it appears to be effortless or 'automatic' requiring no conscious control. This three stage process of skill acquisition is acknowledged in many skill development studies published in various different contexts [Winterton et al. 2006]. However, Winterton et al. also argued that, the demarcation in the stages (or phases) is not very distinct as it appears from definition, in fact, in general sense, ‘skill’ is viewed as just a variable that ranges from ‘low’ to ‘high' ability [Winterton et al. 2006].

Skills are classified as motor skills, perceptual skills and cognitive skills. Motor skills are bodily or manual aspects of performance such as speed, accuracy of physical movements. These skills can be developed through repetition, training, and by obtaining feedback and can be tested in a laboratory setting. The technical or functional skills that are necessary to perform a technical job in a defined area can be included under motor skills. Perceptual skills are related with the ability of interpretation and judgement. Proctor and Dutta listed six different perceptual skills: detection, differentiation/discrimination, recognition, identification, search and memory search [Proctor and Dutta 1995]. These skills could be tested experimentally by observing the participants responses in laboratory experiments. The experiments are designed such that, the participants are required to respond as quickly as possible. The faster response narrows the participants’ response by perceptual skills particularly, by minimising the motor and cognitive skills’ influence on it. Finally, the cognitive skills are referred to as ‘intellectual skills’ by Bailey [Bailey 1996]. These are so deeply intertwined with ‘knowledge’ that they are even referred as ‘knowledge constituents’.

Anderson developed a framework for the cognitive skill acquisition process, similar to Fitts’s three stage skill acquisition process [Anderson 1982]. This framework also consists of three stages; the first and the last stage are declarative and procedural; corresponding to the cognitive and autonomous processes in Fitts’s design, while the middle stage is referred as ‘knowledge compilation’. Anderson defined the knowledge compilation as *“a continuous process of conversion of the declarative knowledge into* *the procedural knowledge"* [Anderson 1982]. While the declarative stage is dedicated more for collecting and understanding the contextual knowledge base (i.e. facts, laws and theories) without applying it, in the knowledge compilation stage one turns his/her attention to critical thinking, problem solving and decision making. Most studies examining the cognitive skills do not consider observations collected in the early phase (or declarative phase) of cognitive skill development and rather concentrate on the 'knowledge compilation' stage. Zoller and Pushkin defined critical thinking, problem solving and decision making as the higher order cognitive skills [Zoller and Pushkin 2007]. They advocated the enhancement of science, in particular the chemistry curricula, with cognitive skills at the focus. Bailey defined problem solving as *"a process of combining the existing knowledge to form new combinations of ideas in order to find a solution to a problem"* [Bailey 1996]. Anderson discussed problem solving as a 'get-oriented ability involving a sequence of cognitive operations' [Anderson 1982]. Wintertone et al. reviewed two ways of examining the development of cognitive skills in problem solving [Winterton et al. 2006]. In the first, the participants were requested to perform a novel task (specifically designed) and their performance was tracked over time to examine the cognitive skill development. Another way was used to investigate the difference in the problem solving strategies between the 'experts' and 'novices', by understanding the conceptually different ways the novices approach the particular problem. Decision making ability is viewed from two different perspectives. Firstly, it is considered as the ability to make choices at each step in the problem solving to obtain an accurate solution. Decision making is viewed as a subset of problem solving. From the other perspective, decision making is viewed as the ability to choose the most desirable option amongst the number of available/applicable alternatives. Therefore, decision making from this perspective is viewed as a situational competence necessary at managerial or authoritative level. The decision making has also been defined as a 'reasoning' or 'emotional process' that can be either rational or irrational [Winterton et al. 2006]. As argued by Wagnor, engaging in the effortful process of thinking is a must in order to develop expertise in any area [Wagnor 1997]. Critical thinking refers to the process of using higher order cognitive skills such as problem solving, calculating likelihoods and decision making to increase the probability of a desirable outcome [Halpern 1999]. By critical thinking, the individual/peer evaluates the outcomes of his/her own thinking process and develops the aptitude of applying the right skill at the right place.

2.5.2 Competence

There is a diverse interpretation of the attribute 'competence' with no consensus definition, as a result, competence is sometimes described as a 'fuzzy concept' [van der Klink and Boon 2002]. Hoffman argued that the rationale for the use of competence determines the definition of competence [Hoffmann 1999]. For instance, Van der klink and Boon situated competence in the socio-cultural practices and refer to 'communication' as an important competence [van der Klink and Boon 2002]. Whereas, Cockerill studied the occupational competence in organizations and addressed 'effective presentation skill' and 'self-confidence' as important competences [Cockerill 1989]. The National Qualification Authority of Ireland (NQAI) defined competence as 'the ability to transfer and apply the skills and knowledge successfully to new situations and environments'. It described three different strands of it [NQA Ireland 2003]. The first strand discussed competence as the ability to play different roles in a professional career such as researcher, team leader or manager in a research group. Such roles necessitated the individual to adapt and work efficiently in their professional career. For instance, at a managerial level, the decision making and team management abilities can become necessary; whereas, as a group member, taking initiatives and self-motivation is viewed as competence. The next strand of competence is dedicated to the abilities of 'learning to learn' by self-awareness [NQA Ireland 2003]. These are identified also as 'meta-competences' and are concerned with the process by which the individual can assess their own knowledge, skill and competence; acknowledge their strengths and limitations/weaknesses; and plan to transcend the limitations through further learning. Nelson and Narens discussed such skills as planning, initiating, monitoring and evaluating one's own cognitive processes; knowledge about learning and problem solving as meta-competences [Nelson and Narens 1990]. The third strand referred to the abilities of individuals to recognize, and reflect on experiences, and engage further in the activity [NQA Ireland 2003]. The strand is referred to as 'insight', as the abilities or competences are achieved by the individual through self - understanding [NQA Ireland 2003]. The individuals interact with the society/ community or surroundings, and examine the feedback received from other people. The feedback from society and the individual's own beliefs formed through experiences and personality enhances the individual's self-understanding.

Some of the competences are considered as context independent and are applicable across different occupations and tasks in general. These typically include literacy, IT skills, communication skills and writing and presentation skills; and are referred to as basic competences.

2.5.3 Knowledge

What constitutes 'knowledge' differs in the natural science and humanistic social science approaches [Cohen et al. 2000]. Natural science contextualises knowledge in a few static groups of procedures, facts and scientific principles that can be recalled. It bases knowledge on empirical evidence gained through direct and systematic observations. In the natural science approach, we may begin with a priori knowledge or hypothesis to explain a particular phenomenon and verify the hypothesis or a priori knowledge by performing controlled experiments. The hypothesis when peer-reviewed and tested becomes a scientific theory. The scientific theory and the set of processes used to test the accuracy and reliability of the hypothesis collectively are regarded as knowledge, though this knowledge is subject to further revision or review but uses empirical or scientific methods for the revisions. The validity of such knowledge is granted only when it is able to withstand the test of experiments and is repeatable [Crotty 1998].

On the other hand, knowledge in human science is understood as a much broader concept that concentrates on the collection and interpretation of experiences, activities and constructs associated with human beings [Creswell 2003]. Knowledge in human science is viewed as a product of interaction between intelligence, i.e. capacity to learn, and the situation (opportunity to learn) but in the process acknowledges the validity of both sensory and cognitive experiences. It refers to the dynamic nature of a knowledge body which is constructed socially. It includes declarative (the knowledge of 'know-that' type) and procedural (the knowledge of 'know-how' type) knowledge but also encompasses the holistic knowledge or understanding and situated knowledge. Holistic knowledge is 'know-why' type of knowledge or related to understanding while situational knowledge is embedded in language, culture and traditions in human science. Knowledge can be applied to a variety of settings, including how to develop further knowledge. In this perspective, it is argued that declarative knowledge precedes the development of procedural knowledge and compiles further knowledge. Anderson argued that the ‘knowledge compilation’ is a continuous process involving the conversion of declarative (knowledge-that) knowledge into procedural (knowledge-how) knowledge using cognitive skills. But a holistic approach in knowledge compilation gives knowledge an additional dimension of personalisation, where the knowledge of the world is constructed by each individual by experiencing things and reflecting on their own experiences [Aderson 1982]. Creswell explained that knowledge possessed by an individual is a product of his/her experience and encompasses the norms by which he/she evaluates new inputs from his/her surroundings [Creswell 2003]. Knowledge therefore is his/her own constructed meanings of any phenomenon from their experiences. An individual can further interact and share his/her knowledge with others and can form a ‘knowledge body’ valid to that particular group of individuals. Unlike the theories in natural sciences that rely on consistency and reproducibility of knowledge claiming that it is universal, the validity of knowledge in human science is related to individual/s, therefore, it is relative and can be valid for that individual/s. With the interpretive or descriptive approaches, one can access the meaning constructed by individual/s and understand the world or phenomenon [Crotty 1998]. Although, one can argue that such knowledge is relative and cannot be justified objectively or theorised, interpretivists claim that one can achieve a wider world-view of the knowledge with such an approach, making such knowledge important [Creswell 2003].

2.6 Review of studies about knowledge, skills and competences in the nanoscience research area

There exists limited literature discussing the knowledge, skills and competences necessary for researching in this research area [Van Horn and Fichtner 2008]. Further, existing literature in this area has focused primarily on the skill needs in relation to the industries associated with nanoscience area and such studies have discussed the technical skills necessary for specific jobs such as process engineers, field service engineers or technical engineers in nanoscience industries. For instance, Singh recommended hands on training of electron microscopy, scanning probe microscopy and knowledge of sol-gel and lithographic techniques for the field service engineer jobs in the electronics industries [Bhat 2005]. Similarly, Abicht et al. discussed the technical skills necessary for the role of 'specialist in nano-surface treatment' [Abicht et al. 2006]. Van Horn and Ficthner, in a qualitative study identified the 'material characterisation skills' and the knowledge of processes related to drug formulations as important skills for research and development officer positions in the pharmaceutical industries in the nanoscience research area [Van Horn and Fichtner 2008]. In another study, van Horn et al. reported the findings of a field study conducted in the nanoscience industries in Arizona, USA [Van Horn and Fichtner 2008]. The study reported that many companies although were not specific about the skills, a few employers mentioned the necessity of acquiring knowledge of more than one scientific discipline. The employers also suggested that researchers working in nanoscience industries should be able to communicate effectively with the scientists of other disciplines. Other similar studies discussing technical skills necessary in the nanoscience area are reported by Crone et al.[Crone et al. 2003] and Pandya et al. [Pandya et al. 2001].

There are many researchers working on a broad spectrum of nanoscience research projects. However, knowledge, skills and competences necessary for researchers working in this area have not been discussed in great details to date. A few studies in the organizational research area examined nanoscience research laboratories to study their functioning from management research perspectives. For instance, Kaplan et al. examined the role of researchers and principal investigators in nanoscience research laboratories in particular. They discussed that researchers play a vital role in coordinating the knowledge across the disciplines in nanoscience research laboratories [Kaplan 2012]. Schmidt discussed a central role of nanoscale instruments in coordinating the knowledge across the disciplines in nanoscience research laboratories [Brune 2006]. They argued that the nanoscale instruments are influential in encouraging the cross talk between researchers working and therefore suggested that the exercise of learning about different instrumentation placed as central facilities in the research centres and/or universities can be initiated as a good practise to foster research collaboration activities. Battard also discussed nanoscale instruments as a ‘central point’ of multidisciplinary nanoscience research, where the researchers from the different scientific disciplines with different research interests and perspectives, can interact with each other [Battard 2010]. However, he argued that in this process, there is a great need for effective communication skills. He argued that the nanoscale instruments have influenced a new knowledge generation in a multidisciplinary platform. However, researchers need to over-explain or over-simplify knowledge to get understood and accepted in another scientific discipline. He claimed that the researchers carrying a dominating disciplinary influence often struggle while explaining the research to other researchers, or even working in collaboration in the nanoscience area. The above studies indicated that although nanoscale instruments although served as the ‘cross-roads’ or meeting points of the disciplines, the researchers needed additional skills to explain their research effectively to others at these cross-roads of disciplines.

2.7 Summary

In this chapter, I discussed the various terms and concepts associated with the research context and reviewed existing literature in relation to the research questions proposed in this thesis. Apart from the few studies regarding knowledge, skills and competences necessary to work in the nanoscience area discussed above, there is an evident scarcity of literature. The inadequacy of information on the knowledge, skills and competences necessary in nanoscience area is a concern and as discussed by Abhichit et al. there is a need of further research in this area [Abicht et al. 2006]. Although the existing literature is important to understand the technical skills necessary for particular roles/profiles in the industries related to nanoscience research, these reports are not adequate to identify the knowledge, skill and competence necessary to work as a researcher in the nanoscience area. It is therefore clear that there is room for further research in this area. The research described in this thesis is aimed at filling the information gap in relation to the knowledge, skills and competences through a phenomenological examination of postgraduate researchers' experiences. Further, from the discussion above, it has been evident the cognitive disciplinarity of nanoscience research is less understood to date. As a result, defining the disciplinarity associated with the nanoscience research area remains challenging. The discussion therefore supports the purpose and aim of this study.

Chapter 3 Research Methodology: philosophical foundations

3.1 Introduction

Pring argued that for a reliable and valid education research, the researcher must develop and present a clear understanding of research questions and employ carefully designed procedures for the data collection and analysis which otherwise can receive a severe criticism [Pring 2004]. In the previous chapters, I discussed the challenges about defining the disciplinarity associated with nanoscience research, particularly when the cognitive aspects associated with it are not fully understood. Further, I discussed that the limited understanding of attributes, knowledge, skills and competences suggests a pressing need to further research this area. This study is designed to shed light on the phenomenon of 'researching in nanoscience' by examining postgraduate researchers' experiences and gain a newer insight of nanoscience research and the knowledge, skills and competences for this area. This in turn will inform the curriculum development in this area. A hermeneutic phenomenological interpretive methodology underpinned by the philosophies of van Manen, Heiddger and Gadamer was applied in this research. The specific methods of data collection and analysis were influenced by the ideas of van Manen and were shaped to best suit the research context and purpose [van Manen 1997]. Hermeneutic phenomenological interpretive is helpful in discovering meaning, gaining understanding and making sense of that which is not yet fully understood [Heidegger 1967]. The present and following chapters are dedicated to explain how the research questions of interest were approached through the methodological framework by discussing the details of the research methodology.

To discuss the theoretical and philosophical underpinnings in an organised manner, Creswell described three elements of a qualitative research design, knowledge claims, strategies of enquiries, and methods of data collection and analysis [Creswell 2003]. When researchers begin their research, they have assumptions about what they will learn (knowledge), how they will learn through the enquiry (epistemology) and how they will write about it (rhetoric). Stating the knowledge claims is simply describing these philosophical assumptions. This research has been carried out in an interpretive realm.

The next element in the research design is the strategy of enquiry or methodology. Like any other novice education researcher, I struggled initially to choose an appropriate methodology from the array of possibilities. Gronewald argued that the researcher needs a grasp of a vast range of research methodologies in order to select the most appropriate methodology(ies) and once chosen, he/she should further undertake a thorough study of the methodology(ies) chosen in order to execute a good research practice [Groenewald 2004]. In the process of understanding different methodologies employed in education research, I was benefited immensely from educational research conferences, workshops and summer schools on qualitative research methods. Discussions with colleagues, researchers and experts working in this area provided me with the opportunity to learn about different methodologies applied in education research. Amongst these, hermeneutic interpretive phenomenology particularly appealed me as a research methodology of lived experiences. In this chapter, I explain the philosophical underpinnings that form the basis of this research and explore the basics of phenomenology, hermeneutics and introduce ‘hermeneutic interpretive phenomenology’.

The last element in Creswell's research design is specific methods of data collection and analysis [Creswell 2003]. The data collection and analysis process in this study is influenced by Heidegger's and van Manen's explanations of the hermeneutic interpretive analysis circle, Gadamer's notion of 'fusion of horizon' and Ajjawi and Higgs' explanation of the analytical steps in thematic coding [Giles 2008; Laverty 2003; van Manen 1997]. To provide an unbiased and equal attention to the philosophical foundations of the research and the practical methods of data collection and analysis, I discussed them in the separate chapters. The following chapter will focus on the specific methods of data collection and analysis applied in this research and will discuss characteristics of the research participants and ethical considerations.

3.2 Knowledge claims

Knowledge claims are understood as the theoretical paradigms with which the researchers begin their research. Wisker described the research paradigms as underlying set of beliefs or principles by which we can enquire and make meaning of our discoveries [Wisker 2001]. This research examines researchers' experiences of nanoscience research and it is carried out in the domain of education research. Cohen et al suggested three paradigms: positivism, critical theory and interpretivism within which education research can be situated [Cohen and Manion 1989].

3.2.1 Positivism

Positivism tends to explain the phenomenon using scientific methods, statistical analysis and value-free, detached observation. Positivism, also known as the scientific paradigm, is based on the ontological assumptions that reality is objective and can be observed as an objective truth. Epistemologically, positivists consider that the objective truth can be deduced by scientific or experimental methods and they tend to offer the same explanation for human phenomena [Cohen et al. 2007]. Crotty explained further that positivists assume that all individuals experience phenomenon in the same way and their perceptions and experiences can be quantified [Crotty 1998]. However, in reality, human phenomena are much more complex and are difficult to be bound or explained fully by detached observations or scientific methods. Each individual can experience, perceive and understand the same phenomena differently therefore experiences, perceptions and understanding are more 'personalized'. One cannot deduce those as 'fact' or 'single reality' as in a positivist tradition. According to Mack there can be many feelings, views and emotions about an event and describing a single objective truth or reality is almost impossible [Mack 2010]. For instance, in my study of examining researchers' experiences, even two researchers may perceive the same research problem differently and can have a different understanding of the same thing.

Further, Bodgdan and Taylor suggested that a positivist when examining a social phenomenon, would be interested in finding the facts and therefore will pay little attention to the emerging multiple meanings of realities from different individuals who experience the phenomenon and construct different meanings of it [Bogdan and Taylor 1975]. A positivist approach supporting objectivity, factual and single reality would not be a right choice for this research as my research demands sufficient attention be given to understand the different meanings constructed by the researchers. The researchers may experience their research differently and perceive and interpret their research and their challenges in different ways. Therefore, positivism does not match to the epistemology of this research. I needed to base this qualitative research with an epistemology that reality can be multiple and gained through exploring personal experiences. Cohen et al. in their later work also commented that positivism is 'less successful' when researchers are studying human nature or social phenomena in education research [Cohen et al. 2007].

3.2.2 Critical theory

Another paradigm suggested by Cohen et.al. [Cohen and Manion 1989] is critical theory. However, this is not a perfect fit for my research for the two reasons: firstly, because critical theory not only intends to understand the phenomena but challenges to critique and change them. My interest in this research is limited only up to examining researchers' experiences of nanoscience research to understand the disciplinarity and skills associated with nanoscience research. I am not intending to advocate, challenge or change the ways researchers' experience nanoscience research. Secondly, critical theory is more often used in the social science domain to understand social issues related with politics, capitalism, democracy, inclusion, etc., none of which are related to my research [Cohen et al. 2000]. The research situated within the critical theory paradigm often reflects the process of critique as well as a clear vision of 'shoulds/oughts' in the proposed policies/practices/theories [Crotty 1998]. In this research, I am aiming to understand the meanings of 'researching in the nanoscience area', and later with this understanding discuss the disciplinarity and attributes associated with nanoscience research. Such understanding can inform to curriculum development in this area. These are not 'shoulds/oughts' but the outcomes/suggestions resulting from my interpretive engagement with the researchers' experiences or life worlds.

3.2.3 Interpretivism

Interpretivism emerged in order to understand the complex world of human experiences [Crotty 1998]. Researchers in an interpretivist tradition do not seek some kind of absolute or real knowledge through scientific methods, rather they acknowledge the processes which involve interpretations to get closer to the different meanings that people construct about their own realities [Crotty 1998]. Interpretivism was developed as a reaction to positivism and is also known as the anti-positivist paradigm [Mack 2010]. It is influenced by the philosophy of hermeneutics meaning interpreting the meaning of the text, and the philosophy of phenomenology that professes the need to study individuals' perceptions of their world as a starting point to understand complex human phenomena [Cohen et al. 2007]. As the emphasis in interpretivism is on understanding individuals' perceptions of phenomena, there could be different meanings associated with different individuals.

Walsham commented that the epistemological position of interpretivism is that 'the reality is socially constructed by human actors' and the enquirer uses his/her perceptions in order to guide the process of enquiry [Walsham 1995]. William suggested that basing the research in the interpretive paradigm, a researcher can apply qualitative methodologies to obtain explanations of the actions from actors themselves, or observe their actions and interpret [Williams 2000]. According to Erickson, the qualitative study within the interpretivist paradigm should focus on the meaning and further how to interpret those meanings with the researcher's epistemological inputs [Erickson 1986]. Smith and Oshborn, in this relation argued that understanding the meaning involves a two-stage interpretation process. In the first stage, the participants make sense of their world, while in the second stage, the researcher will assimilate participants' understanding [Smith and Osborn 2008]. However, they said that the researcher should also be careful not to influence the interpretation by his/her own perceptions and take an objective stance. Although, as taking such an objective stance is difficult in the interpretive process, interpretivist research is sometimes criticised by positivists. The notions of reflexivity/reflective quality in the hermeneutic process of interpretation are discussed in defence to that. In this way, the interpretive researcher is constantly questioning his/her beliefs and influences, and reflecting on them in the process of inquiry. Therefore, he/she has a basic awareness of his/her biases and how these can impact on the process of enquiry [Laverty 2003]. The researcher can present a discussion of his/her reflective engagement with the enquiry through writing in the interpretive research. Van Manen argued that with reflective practice, the researcher can employ his/her own similar experiences in the process of inquiry [van Manen 1997].

Cohen et al. argued that interpretivism is dominant in exploring human phenomena [Cohen et al. 2007]. They discussed that the role of a researcher in interpretivist tradition is "*to understand, explain and demystify (or interpret) social reality"*. My research is set to examine researchers' (human actors) experiences of nanoscience and therefore the interpretive paradigm is appropriate to situate my research work. In this research, I am not just limited to observe and explain how postgraduate researchers' have experienced nanoscience research, I am also intending to interpret and understand their experiences. Such commitment to the interpretation and understanding can be explained well within the interpretive paradigm.

I am involved in this research as a postgraduate researcher. I had experienced many similar situations/events in my own research which at times resonated with my researchers' experiences. It is unrealistic to bracket or suspend my experiences and knowledge in this research. Instead, my experiences as a postgraduate researcher can guide the interpretations of researchers' experiences and enhance my understanding of their experiences (Heidegger quoted it as "*reader's understanding of participants' understanding of their experiences*" [Laverty 2003]). It was possible by employing my own experiences in the process of inquiry as suggested by van Manen [van Manen 1997]. In a nutshell, hermeneutic phenomenology in interpretive paradigm fitted in the harmony of the research.

While explaining the knowledge claim in an interpretivist manner in this research, it would be untrue to say that the researcher is aiming for a complete understanding or the final word on particular research questions [Giles 2008]. I am aware that the ontological assumptions of interpretive paradigms are based on relativism, according to which the reality is constructed by individuals' interpretation, and it can be different for every individual and cannot be generalised. Therefore, in this inquiry, I am not claiming to generalise the postgraduate researchers' experiences and attain a complete or final understanding of it. However, I certainly believe that even with the selected participants, the hermeneutic phenomenological examination in an interpretive paradigm can provide glimpses of those range of perceptions and understanding of the phenomenon which are not appreciated yet in identifying the meaning of 'researching in nanoscience'. Therefore, this research can contribute something new in the deeper understanding of nanoscience research. The rigour of the research cannot be evaluated through the positivist lens.

3.3 Strategies of Enquiry: methodology

The qualitative approach is used dominantly in social science research for the exploration of human experience, perceptions and behaviours [Cohen et al. 2007]. Patton supported the qualitative approach by stating that *"human experiences are descriptive in nature and can be illustrated only qualitatively"* [Patton 2002]. He explained further that the qualitative approach can successfully explore the 'life worlds' or lived experiences. My interest in examining postgraduate researchers' experiences and thereby their perceptions, interpretations and understanding of nanoscience research emphasises the need for a qualitative approach in this research. The researchers' lived experiences, in other words, their everyday experiences of nanoscience research could be examined using different qualitative methodologies such as case studies, narrative research and phenomenology.

Methodology brings practicality to any research by specifying the approach, theoretical paradigms and methods of data collection and analysis. This research applied hermeneutic interpretive phenomenology guided by the writings of van Manen, Heiddger and Gadamer. Semi-structured interviews were applied as the specific method of data collection. Data analysis method was shaped following van Manen's methodological guidelines, Heidegger's ideas of hermeneutic analysis circle, and Ajjawi and Higgs' explanation of thematic coding in the phenomenological research analysis. Van Manen M. wrote that through an examination of lived experiences one can identify the 'meanings' associated with it [Barnacle 2004; van Manen 1997]. Phenomenological research does not claim a meaning in advance, instead, by studying the phenomenon through the experiences of the people who have lived it, it allows the possibility for new meanings to emerge [Crotty 1998]. This approach makes phenomenological research different from other empiricism or rationalism approaches and situates it in the interpretive domain. In the methodological framework of hermeneutic phenomenology in this research, I am examining researchers' lived experiences and understanding the emerging new meaning of nanoscience research.

In the following section, I describe phenomenology and its two main approaches: descriptive and interpretive. My interest in this thesis is particularly in hermeneutic phenomenology which follows an interpretive approach. I explain the work of Heiddger, Gadamer and van Manen which underpinned the hermeneutic interpretive phenomenological research methodology. The specific methods of data collection and analysis are explained in the following chapter.

3.3.1 Introduction to Phenomenology

Phenomenology is derived from a Greek word 'phenomenon' meaning 'to show up' [Husserl 1970]. The 'phenomenon' can be anything: an event, a feeling, an idea, a person or even a place. Cohen *et al.* described phenomenology as the study of phenomena or the appearance of things [Cohen and Manion 1989]. Van Manen argued that a phenomenon can be a real or imagined object, a feeling, idea or an emotion which presents itself to consciousness [van Manen 1997]. Husserl, the German philosopher and psychologist known as a 'pioneer of phenomenology' described phenomenology as a descriptive science of first-person perspectives.

Phenomenology is associated with the exploration of the 'phenomenon' which can be reached through peoples' experiences. Van Manen therefore argued that *"the study of a phenomenon is the study of lived experiences"* [van Manen 1997]. Langridge described phenomenology as the examination of the experiences which human beings live through [Langridge 2007]. He discussed that a descriptive account of lived experiences included how the phenomenon was experienced by an individual or individuals. Phenomenology was soon recognized in the literature for its strength in the collection of descriptive experiential accounts. Soon after the origin of phenomenology, due to the efforts of its later exponents, there appeared some adapted distinct forms of phenomenology which extended its power of collecting descriptive account with an additional interpretive dimension [Sadala and Adorno 2002]. As a result, phenomenology also appeared as a research approach or a methodology in interpretive studies. Phenomenology now has two distinct traditions or approaches: descriptive and interpretive. Although, the interpretive approach was introduced later, both descriptive and interpretive approaches remained equally dominant in the study of human phenomena [King 2011]. The choice of a particular phenomenological approach should be made by the researcher following their particular research interests, the nature of investigation and by reviewing the philosophical underpinnings of each approach to decide which is more suitable to the circumstances of the research.

Descriptive phenomenology is also identified as Husserlian phenomenology or as transcendental phenomenology [Smith and Osborn 2008]. Interpretative phenomenology is associated with German philosopher Martin Heidegger and is also identified as Heiddegerian phenomenology [Langridge 2007], as hermeneutics [Barnacle 2004] and as existential phenomenology [Langridge 2007]. Many other philosophers, including Merlau Ponty, Jean-Paul Sartre, Hans Georg Gadamer, Amedeo Giorgi, Paul Ricoeur and Max van Manen further contributed to these two approaches of phenomenology [Cohen et al. 2007; Creswell 2003]. Before discussing the distinctions in the two phenomenological approaches, it is important to emphasize that a common principle in both is that they try to make explicit what people have lived through in their life world. Therefore, experience is a key for both phenomenological approaches [Langridge 2007]. The two approaches reflect the different ways in which life worlds are explored. I discuss the highlights of descriptive and interpretive phenomenological approaches in the following sections.

3.3.2 Descriptive phenomenology (Husserlian phenomenology)

Descriptive phenomenology includes a strong emphasis on ‘consciousness’ [Cohen et al. 2000; Husserl 1970]. Edmund Husserl believed that to understand the nature of human knowledge, the objective or scientific measurements are not sufficient. He commented that human beings have subjective experiences which cannot be reduced completely to a measurable object. Although, Husserl didn’t completely discard objectivism, he tried to fill the gap between objectivism and the subjective experiences that people have by describing the ‘objects’ of consciousness. He proposed that one should focus on the experiences of human beings through these objects of consciousness. Husserl’s claim was that ‘whatever a human being knows is based in his /her consciousnesses’. He argued that the consciousness is always ‘consciousness about something’, thus, consciousness is associated with the ‘objects’ of consciousness. From Husserl’s perspective, for phenomenological investigation, the objects of our consciousness have existence in some form, for example, they can be actual physical objects, or abstract concepts. He discussed that our thinking and perceptions are directed towards these objects of consciousness and discussed such directedness of our consciousness under the notion of ‘intentionality’[Husserl 1970, Creswell 2003]. He argued that we can access and analyse these objects of consciousness [Laverty 2003]. Husserl discussed phenomenology as the examination of the consciousness or phenomenon that appears to the consciousness. He argued that our knowing of the world is through this consciousness [Molla 2010]. Although, Husserl's notion of the separate existence of the objects of consciousness independent from our thinking was questioned by some of the later followers of phenomenology, the power of this approach to explore human being's experiences of the particular phenomena was also acknowledged by many. For instance, Creswell commented that the descriptive phenomenological approach is best suited to recognize the some of the common or shared experiences of people about a phenomenon [Creswell 2003].

Descriptive phenomenology calls every day experiences 'life worlds' and considers that phenomenology is situated within these life worlds [Cohen et al. 2000; Heidegger 1967]. The life world experiences, or lived experiences, are taken for granted most of the time. Husserl suggested that to explore the life worlds, one should stop taking for granted the things perceived about the phenomenon, or in other words, 'bracket out' them and take a look at phenomenon again [Smith et al. 2009]. 'Bracketing' or 'reduction' is a critical feature of descriptive phenomenology [Hyncer 1985]. It entails setting aside one's assumptions, beliefs or views so that the data collection is not biased by one's own beliefs, or views about the subject under investigation. The researcher applying a descriptive phenomenological approach is interested in collecting the descriptions of the 'phenomenon' actually lived and experienced by the participants. While doing so, he/she should bracket any pre-existing knowledge of it, irrespective of where it comes from (common sense or with scientific evidence). Once these descriptions are obtained, the researcher can conduct a dissection of the descriptions to discover the 'essences' or central meaning of the phenomenon. Once the essences are obtained, the descriptive phenomenologist considers his/her work done [Laverty 2003]. Such essences or central meanings are said not been affected by the beliefs or experiences of the researcher conducting the study following the descriptive phenomenological approach. If the researcher aims to collect the description of the phenomenon and transpose his/her own insight in to the text to derive the central meaning of the phenomenon, it departs from the descriptive phenomenological approach.

3.3.3 Interpretive phenomenology (Heideggerian phenomenology)

The interpretive phenomenological approach is also concerned with the lived experiences and deriving meaning however, it differs in the way the exploration of the lived experience proceeds [Laverty 2003]. The interpretative phenomenological approach does not just describe the experiences, but, it is also concerned with their interpretation to understanding the meaning or central essence of the experiences. It requires developing a conversational relationship with the phenomenon. Such a conversational relationship influences exploring the phenomenon and allowing emergence of the renewed or new constructions of meaning [van Manen 1997].

In descriptive phenomenology, Husserl focused on understanding the phenomenon by examining the objects of consciousness and describing how meanings are presented to our consciousness. However, Heidegger has argued on it saying that "*Our acts in the life world are so transparent that they do not even pass through the consciousness"* [Groenewald 2004; Heidegger 1967]. He also argued that our knowledge of the world exists even before we are consciously aware of it and that we aren't different from the world, rather we are present from the beginning amongst the world as 'beings'[Groenewald 2004]. From Heidegger's view point, phenomenology is focused on identifying the 'situated meaning in the world' with the perspective 'being in the world' or *'dasein'* [Heidegger 1967; Laverty 2003]. He suggested that even our thinking are 'beings' of the world, and they cannot be separated from the world we live in. In all, Heidegger's approach to phenomenology is that one cannot make sense of their world by remaining detached from it. Hence, a key difference in the descriptive phenomenology and interpretive phenomenology lies in the degree to which presuppositions, views or beliefs can be suspended. While bracketing of presuppositions and beliefs is considered critical in the descriptive phenomenological approach (Husserlian phenomenology), the interpretive phenomenologist does not believe that the presuppositions or views can be set aside, reduced or bracketed. They believe that we are in the world with the things we observe, our knowledge of the things is also a part of our beings [Smith et al. 2009].

In other words, interpretivist believes that the interpretations in a phenomenological study are unavoidable [van Manen 1997]. From Heidegger's perspective, interpreting the meaning of the things (or the experience) is important so that it can be conveyed or carried further in the process of interpretation. As experience is not a separate entity than one's world, the historical and cultural context of the experience becomes important to understand. Similarly, the language used to identify the meaning is important in this process as the experience is not just described but interpreted [Langridge 2007]. In this regards, the association of phenomenology with hermeneutics offered a great deal in this interpretation process by allowing the historical, cultural context and language to be involved in it.

Hermeneutics is related to 'deriving the meaning' [Moustakas 1994] or 'to interpret' [van Manen 1997]. The word 'hermeneutics' was derived originally from a Greek word 'hermes' meaning the 'messenger of the god' in the mythological literature. Hermes was responsible for transforming and communicating complex knowledge into a form which humans can understand. Hermeneutics provides a description of the meaning that individuals attach to their lived experiences within a meaningful social, cultural, political and historical context [Rapport and Wainwright 2006]. In other words, hermeneutics can retain the connection with the social, cultural or historical context within which the meaning was constructed and the phenomenological approach can further interpret the meaning [Cohen et al. 2007; Groenewald 2004]. The interpretive phenomenological approach combined with hermeneutics was simply called 'hermeneutic phenomenology'[Crotty 1998]. It emerged mainly from the work of Heidegger but Sartre, Gadamer and van Manen also contributed to this approach.

Sartre, who was influenced by Heidegger's work, acknowledged the ideas of 'being in the world' (or *'dasein')* and the process of interpretation discussed in Heideggerian phenomenology. He further suggested the importance of interpersonal aspect of experience arising with the involvement of other people. He considered that the 'being' is a dynamic process and the presence or absence of other people can have impact on the 'being'. He argued that the involvement of other people make the individual's experience interpersonal and more complex as people continuously communicate with each other and develop a mutual understanding, therefore such interpersonal aspects cannot be neglected [Smith, Flowers and Larkin 2009].

3.3.3.1 Gadamer's notions of hermeneutic phenomenology

Gadamer followed Husserl's and Heidegger's work in phenomenology. Gadamer was interested in 'language and its association with the world'. Gadamer considered that language and understanding are inseparable and language facilitates understanding [Gadamer (1975/reprint 1996); Laverty 2003]. His contributions to the hermeneutic interpretive phenomenology are the notions of 'horizon of understanding' and the ‘hermeneutic circle’ which are also explained later by van Manen in his work [van Manen 1997].

Hermeneutic circle

Heidegger described the interpretive process as a circular process requiring moving back and forth between the text, thereby moving between the historical contexts of time in order to achieve a greater understanding of the whole experience. Gadamer continued this idea, and described further, the circular interpretive process with the term ‘hermeneutic circle’. Hermeneutic circling is an art of understanding lived experiences [Gadamer (1975/reprint 1996); Patton 2002]. Gadamer explained how the lived experiences can be understood more and more clearly by engaging with the text of the lived experiences through the interpretive circle [Giles 2008]. He explained that the hermeneutic circle allows a relationship between the readers (of the text) with the text itself [Giles 2008; Laverty 2003]. The more readers are engaged with the text in the hermeneutic circle, the more they interpret and understand it. Gadamer argued that in the hermeneutic circle, the reader approaches a part of a text and interprets it with respect to an imagined whole which is not yet known. As the process of engaging with the remaining other parts continue, the readers understanding change continuously. The circularity of such an interpretive process continuously adds more understanding of the meaning of the whole, as well as, parts of the text. In the hermeneutic circling, unlike the Husserlian approach, the assumptions, judgements or beliefs are not bracketed. Instead, they are beings or initial understanding which can be changed through the interpretation process. Gadamer specified that not all beliefs are negative, they can be positive or legitimate and hence bring a genuine understanding [Newmann 2013]. He also discussed a concern of falling in the endless hermeneutic circle of interpretation. He argued the understanding achieved at any stage in a hermeneutic circle becomes a fore project for a further understanding leading to a never ending interpretation process. However, both Heiddger and Gadamer also discussed that one can attain an understanding in a hermeneutic circle by undergoing through some rounds of interpretation and without jumping to any conclusions earlier.

Fusion of horizon of understanding

Gadamer's notion of expanding the 'horizon of understanding' is another important contribution in hermeneutic interpretive phenomenological approach. Gadamer has described the notion of fusion of the horizon of understanding as a process of increasing the possibilities of newer understanding[Gadamer (1975/reprint 1996).]. In this process Gadamer explained that the interpretation attained each time becomes a fore project to build newer understanding. Also, the interpretation and understanding cycle can involve more subjects experienced similar phenomena. In hermeneutic phenomenology, the descriptive text of experiences collected from the participants is important to interpret their experience of a phenomenon, but at the same time, researcher's own experiences of that phenomenon are also considered important in the interpretive process to achieve newer understanding of the phenomenon. When the researcher is exploring the phenomenon in light of the participants' experiences, the horizon of the participants' experiences is fused with the horizon of the researcher's own understanding to allow the researcher to understand the experience in its true dimensions. As Gadamer argued, the researcher's present understanding (from his/her own experiences or prejudices) is his/her present horizon. To understand participants' experiences, the researcher needs to transpose him/herself into the horizon of the participant. Blending, or fusion of horizons, allows the elucidation of the phenomenon to its best [Whitehead 2004]. Gadamer discussed it as *"to see it better, within a larger whole and in true proportion"* [Gadamer (1975/reprint 1996).].

3.3.3.2 Van Manen's ideas of hermeneutic phenomenology

Van Manen's approach is similar to Gadamer's approach of hermeneutic phenomenology. Although, van Manen agrees that there are no defined procedures or methods for a phenomenological research study [van Manen 1997]. He emphasized the idea that, the researcher instead of being very stagnant about it, should invent appropriate research methods, techniques and procedures for their own research problem without losing the qualitative rigour [Giles 2008]. His research in hermeneutic phenomenology has also drawn some practical guidelines for a hermeneutic phenomenological research.

Van Manen explained hermeneutic phenomenological research as an attempt to construct the interpretive descriptions of the life world. He discussed that the researchers can be aware of the fact that the life world is complex, and a full or complete description of it is unattainable. However, with a deeper attunement to the life world of the participant, there is a hope to understand it in a better sense [van Manen 1997]. He also discussed that 'a real understanding of phenomenology can only be accomplished by actively doing it'.

Reflexivity

By opposing the principle of bracketing, van Manen supported the 'reflections' and/or 'reflexivity' in relation to the hermeneutic phenomenological research [van Manen 1997]. Reflection or reflexivity is considered in the research in two ways. The first way is participants' reflection on their experiences while the second way is related with how the researcher brings his/her own experience of the phenomenon, beliefs and understanding in the process of data collection and analysis.

The participants' reflections are re-collective in nature, and can be obtained during the interview process by asking questions to them and encouraging them to think about their own experiences. Reflexivity in hermeneutic phenomenology is described as a process by which the researcher participates in the phenomenological inquiry, but in such a way that he/she is conscious about the ways in which his/her questions, methods and beliefs might impact on the research data collected or knowledge produced in the study [Langridge 2007]. Through reflection/reflexivity, the researcher can apply his/her relevant prior experiences or understanding of the phenomenon as an aid while collecting the research data from the participants. Also, the researcher's prior experiences or understanding of phenomenon can be functional in examining the research data and/or in the construction of the meaning of the interpretation, however, it is equally important to remain aware of them [van Manen 1997].

Interpretive writing

Heidegger suggested that a continuous engagement of the researcher with the research data is achieved by 'thinking and dialoguing with it continuously'. He supported the idea by saying *"thinking is a bodily 'being in the world' experience"*[van Manen 1997] Van Manen emphasized the importance of the researcher's engagement in the writing process in hermeneutic phenomenology. He commented that *"writing is a method in hermeneutic phenomenological research"* and *"research and writing are aspects of one process"* [van Manen 1997]. Van Manen supported the interpretive writing as a dialectic art of writing where the researcher is in continuous relationship with the data as he/she writes his/her understanding. The writing and/or re-writing continues until the researcher considers that the 'essence' or 'central meaning' of the experience is captured. The essence or central meaning is the heart of the phenomena without which its description is incomplete. Following the essence of both Heiddger's and van

Manen's writing, it is clear that research in the hermeneutic interpretive phenomenological tradition is a journey of 'thinking and writing' about the research data and such thinking is stimulated by researchers engagement with the research data through reading, writing, talking, reading, re-writing, re-talking in a circular manner [Giles 2008].

3.3.4 Following van Manen's footsteps in the hermeneutic phenomenological research

My commitment to the exploration of meaning and understanding of the phenomenon of nanoscience research in this study can be associated with the Heideggerian approach to hermeneutic interpretive phenomenology and it embraced the need to studying researchers' lived experiences of nanoscience research.

Inspired by van Manen's ideas of hermeneutic phenomenology, I reshaped the methods of data collection and analysis (explained in the following chapter) to fit to my research requirements. While doing so, I followed the philosophical notions of Heiddger M., Gadamer and van Manen. Last but definitely not the least, I conducted this study while keeping in mind the research questions, research participants and the nature of inquiry. In this thesis, I refer to hermeneutic interpretive phenomenology as a research methodology.

3.4 Phenomenology in education research

Van Manen wrote that *"an understanding of phenomenology can be accomplished by actively doing it"* and commented that doing phenomenological research is a lived experience by itself [van Manen 1997]. Many education researchers conducting phenomenological studies shared reflective accounts of their experience of doing phenomenology [Baird 1999; Barnacle 2004; Thomson 2008]. It is fruitful to explore such studies to know more about phenomenology in education research and how researchers experienced phenomenological research.

Specific phenomena in education such as learning, skill development, students' engagement in the classroom and teachers' approaches to teaching/curriculum design received much attention from researchers in the education realm [Cohen et al. 2000; Cohen et al. 2007; Crotty 1998]. These phenomena were researched by delving deeper into the students', teachers' or lecturers' life worlds and thereby examining their feelings, beliefs, convictions, perceptions and understanding [Baird 1999; Barnacle 2004]. The descriptive phenomenological approach has been applied to describe some such phenomena in education research and to understand its essences from the participants' life worlds [Laverty 2003; Ostergaard et al. 2008]. Adding an interpretive dimension to the phenomenological approach and combining tools/methods for data collection and analysis with this approach resulted in restructuring phenomenology, as a newer approach and a complete methodology [Moustakas 1994]. The interpretive dimension also allowed the researchers to apply the phenomenological research methodology in education research to inform the policy/curriculum development activities in education [Giles 2008]. In this section, I summarized some recent phenomenological research in education. There are examples of both phenomenology applied as an approach and as a methodology. Although, their particular research contexts were not always relevant to my research, I was fascinated by the idea of knowing their lived experiences of conducting phenomenological research.

Pascal et al. discussed their experiences of applying hermeneutic phenomenology as a research methodology in health education [Pascal et al. 2011]. The first author in the research paper was involved in supervising the other three co-authors during their postgraduate research. Postgraduate researchers were engaged in health education and were using hermeneutic phenomenology as a research methodology. All three postgraduate researchers described the emergence of themes around the 'being-with' perspective of Heidegger's phenomenology in their research. Further, the researchers themselves experienced how 'being-with' was central in their life worlds as a researcher. They described that their research performance enhanced due to their interactions with supervisor and colleagues, thereby, 'being-with' the research community and in the academic environment had a positive influence on their journey as a researcher. The supervisor has also experienced that her way of 'being-with' the researchers helped her in expanding her phenomenological horizon. The research suggested importance of reflecting on the experiences of conducting research and sharing those accounts with others.

Thompson carried out a phenomenological study with the descriptive approach to examine students' experiences of a course module [Thomson 2008]. The module 'reading and writing academic text' was designed specifically to address the academic literacy of the students by an examination of participants' (teachers') experiences of undertaking the course module. Examining the teachers' lived experiences of undertaking the module, she concluded that her assumptions about the module were not all correct. She commented that students undertaking this module were embodied with the module so passionately as if they infused 'life' in it and made learning much more fascinating and far better than expected. Therefore, she suggested that the teachers teaching in a classroom should look beyond the predefined set of outcomes and focus at such 'live' reality.

Ouyang studied Taiwanese parachute students' (students who are sent to study in the USA unaccompanied by their parents) experiences of being and studying in a foreign land [Benjamin 2004]. The author's own lived experiences of being a parachute student added further depth to his interpretation of the students' lived experiences. He acknowledged a deep appreciation for hermeneutic phenomenology as a research methodology for providing new ways of interpreting and understanding the emerging new meanings of his experiences. He also argued that the interpretive writing brought a deep sense of satisfaction and fulfilment to him in his own life by knowing more about himself as a parachute student.

Other phenomenological studies were carried out to examine teachers' experiences in schools, or lecturers' experiences in a higher education context. These studies indicated the strength of the phenomenological approach/method in examining the teachers' experiences of teaching, or teachers' experiences as mentors. For example, Silen was interested in studying the tutor's 'way of being' and thereby understanding its relevance to learning for the students in a problem based learning (PBL) classrooms [Silen 2006]. She conducted a phenomenological study to examine tutors' lived experiences of tutoring in a PBL classroom and concluded that it is essential for a tutor in a PBL classroom to understand the significance of 'approach' in a class to enhance students' learning. This approach was described as a combination of the tutor's physical presence and attention to students' discussions. She argued that the tutor should experience the learning process 'as a learner' and 'as a tutor'. Her research also informed the tutor training programmes. Willis applied a hermeneutic phenomenological method to review his own work as a lecturer in education and concluded that the phenomenological study provided an enriching contribution to his understanding about himself as a lecturer and provided a newer perspective on his approach to education. [Willis 2001]. Gliles conducted a hermeneutic phenomenological study to understand the essential meaning of 'student-teacher relationship' by examining the teachers' and students' experiences in an educational institute [Giles 2008]. His study indicated the importance of deepening sensitivity of teachers' relational experiences with students and the findings informed teacher educational programmes with guidelines to revise the content and pedagogic considerations of such programmes. Gayle conducted studies with hermeneutic phenomenological research methodology influenced by van Manen's notions, to examine undergraduate nursing education students' experiences [Gayle 2007]. She examined undergraduate students' lived experiences to understand the phenomena of how nursing students connect with their patients through spiritual nurturing to inform the pedagogic perspectives of nursing education programmes. Her research brought to attention the effects of clinical environment on the students' spiritual health. The interpretive study also offered some suggestions to enhance spiritual nurturing of nursing students through pedagogic practices and thereby bring positive changes in adjunctive therapies the students offer to the patients in practise. Osetrgaard *et al.* reviewed different studies in science education and categorized them under three approaches of phenomenology: 1) phenomenology *of* science education 2) phenomenology *in* science education and 3) phenomenology *and* science education integrated [Ostergaard et al. 2008]. The first approach, phenomenology of science education was particularly relevant to this study. It involved a detailed section titled 'focusing on teachers, and teachers' experiences' which summarised the phenomenological studies associated with examining teachers' experiences of teaching. It discussed a study conducted by Baird with twelve science teachers to examine their experiences of 'being a science teacher' [Baird 1999]. The examination of accounts of teachers' experiences brought into light the new emerging meanings of 'being a teacher'. Further, the study suggested that the practices including 'giving regular opportunities to reflect upon the professional practice' can allow the teachers to improve the quality of their work.

The literature above suggested that phenomenology, as an approach and as a methodology (hermeneutic) found a promising place in the education research. Further, hermeneutic phenomenology is successfully used to examine teachers', students', researchers' and lecturers' life worlds and to explore the complex phenomena associated with them. Barnacle commented that phenomenology could play an important role in informing as well as transforming other models of inquiry promoted by positivists and strongly recommended its use in the education research [Barnacle 2004].

3.5 Summary

This chapter described the three elements of the qualitative research design, knowledge claims, strategies of enquiries, and methods of data collection and analysis of this research. In order to reaffirm the hermeneutic phenomenological endeavour of this research, I describe this research as a journey collecting, describing and interpreting postgraduate researchers' experiences of nanoscience research in order to understand newer emerging meaning of the phenomenon of researching in nanoscience. In the following chapter, I discuss the particular methods of data collection and analysis applied in the hermeneutic interpretive phenomenological methodology. Furthermore, I present the measures taken to assure the trustworthiness and rigour in this interpretive research.

Chapter 4 Research method in action

4.1 Introduction

Van Manen wrote "*The method of phenomenology and hermeneutics is that there is no method"* and argued that one should discover or invent the method in response to the fundamental research question in hand [van Manen 1997]. In essence, van Manen advocated that researchers should orient themselves towards the phenomenon of interest instead of worrying too much about the research technique. However, he also argued that it (the method) should not be a casual approach and the researcher should be in a position to articulate his/her understanding of the philosophical underpinnings on which he/she has structured the particular method used for the research. In the previous chapter, I explained the philosophical underpinnings of phenomenology and hermeneutics which combine in the hermeneutic interpretive phenomenology- the methodology chosen for this research. The writings of Heiddger, Gadamer and van Manen influenced me in this exploration of lived experiences. Van Manen's notions of 'hermeneutic interpretive phenomenology' particularly informed the research data collection and analysis process. This chapter describes the research participants in this study and explains the specific methods of research data collection and analysis. Information on the ethical considerations has also been included in this chapter. Van Manen also argued that *'Doing hermeneutic phenomenological research itself is a lived experience'* [Giles 2008] and reflecting on that experience adds value to the research undertaken. He also advocated that the method could be guided by the researchers' own experiences and reflections. Adopting van Manen's hermeneutic interpretive phenomenological methodology, I believe that my own experience as a postgraduate researcher in education, my understanding as a teacher and my reflections on my own experiences of conducting this research can be resourceful to guide the research process. These can evolve the methods of data collection and analysis and thereby add value to the research undertaken. Following van Manen's arguments discussed above, I took the liberty of tailoring my methodological approach to best suit the research purpose. I included the decision trails in the development of data collection and analysis to explain how van Manen's notions were adapted in the actual research process.

4.2 Research participants

This research examined postgraduate researchers' experiences of nanoscience research. There are approximately 300 postgraduate researchers pursuing their research in the nanoscience related research areas from different institutes and universities across Ireland [O'Keeffe 2009]. Considering the in-depth nature of phenomenological interviews and their subsequent analysis in hermeneutic interpretive phenomenological circle, it was essential to limit the sample set that could give enough time to analyse the research data [Hyncer 1985]. At the same time care is taken such that the research sample size should not appear 'less credible' to policy makers if they compare the study with quantitative data or surveys. Twenty-five postgraduate researchers participated in this qualitative research as interview participants. I explained below the process of selection of research participants and why I decided to include twenty-five participants for the study.

Initially, I collected postgraduate researchers' contact information from nanoscience conference abstract books, journals and proceedings published since March 2010. An updated list of personnel working in the nanoscience area based in different educational institutes, research institutes and universities in Ireland was subsequently published by FORFAS in the 'Ireland: Nanotechnology Commercialisation Framework' report in October 2010 [Forfas report 2010]. I contacted the principal investigators and requested them to provide the contact information of postgraduate researchers currently working in their research groups. Once I had this information, I contacted postgraduate researchers directly through email. I provided them sufficient details about my research objectives and interview structure and invited them to participate in the study. In this email, I also asked them to provide some basic information on their academic profile (graduation discipline, starting year of postgraduate research and prior research experience). I also requested them to provide some information on their current research project such as research project title and area of research. Finally, I requested them to convey if they are interested in participating in the interview. Sometimes I followed the 'snowball sampling' method in which I asked the interested participants to suggest names of a few other postgraduate research colleagues for this study and thereby expanding my research data set [Groenewald 2004]. I received positive responses from 50 participants. I developed a database of information based on the responses of postgraduate researchers to my email. I conducted interviews with twenty-five postgraduate researchers and involved remaining postgraduate researchers in a quantitative survey conducted at a later stage in this research.

An important consideration in the research sample selection (for interview) was to ensure variation in terms of following categories:

- Postgraduate researchers' graduation discipline;
- Starting year of postgraduate research/PhD study;
- Area of research within nanoscience area;

- Institute/ university;
- Prior research experience.

Amongst the list of participants (postgraduate researchers) available for the interview, I choose 6 participants for a pilot study and 25 participants for the final interviews. The selection was performed in such a way that the sample set represented maximum variation in each of the categories above. I then requested the selected postgraduate researchers to email me their recent conference abstract/s, or publications, or alternatively a short description (about 6-7 lines) of their research project. This information provided me some prior idea about their current research.

In relation to the number of participants, Laverty commented that in phenomenological studies, there cannot be deciding criteria for minimum or maximum number of research participants for the interview [Laverty 2003]. She argued that the number of participants may vary depending on the nature of study and the researcher should continue the exploration until they reach to a conclusion that no clearer understanding of the phenomenon can be achieved by any additional interviews. Although with the extensive nature of phenomenological research and the given time frame of the research, there was a certain limitation on the number of participants possible. However, following Laverty's advice, I decided to conduct the analysis of the interview transcripts in parallel with the data collection, which allowed me to determine if the themes derived from the analysis were repetitive or I was still encountering something new each time. It also allowed me to determine when to complete the interview process and work on the data analysis with all the transcripts collectively. After twenty-five interviews I started noticing repetition of the analysis themes in the transcripts and therefore I decided to stop conducting further interviews. It is important to mention that my claim is not that the analysis of twenty-five interviews will derive a complete understanding of the phenomenon of 'researching in the nanoscience area'. Analysing experiences of twenty-five participants, one may argue that it is not possible to explicate all possible themes but they were sufficient to capture enough aspects of the phenomenon. I fully understand that the lived experiences are complex as each participant has a different life world and the interpretive analysis can go on endlessly. It is also necessary that the researcher has to remain pragmatic and at a certain stage decide where to stop the process of interpretation [van Manen 1997]. Through the analysis of the research data obtained in these interviews, I am hoping to derive the essential meanings of the phenomenon of 'researching in the nanoscience area' and thereby gain newer or at the least a broader understanding of it.

4.3 Data collection method

The method chosen for data collection (semi-structured interviews) has been guided by the existing literature in this area, the work of other fellow researchers and my own reflections and experiences. I discuss the existing literature in the context of data collection first followed by how the actual data collection process applied in this thesis was shaped.

4.3.1 Literature guided shaping of data collection method

Van Manen suggested that there are many methods of data collection for the analysis of lived experience. However he has particularly favoured the 'interviews' in the phenomenological studies as the interviews facilitate the reflective recollections of the research participants [van Manen 1997]. Bailey described the informal open ended interviews as a conscious effort to collect the rich lived experiences [Bailey 1996].

Hyncer discussed some guidelines to conduct open ended phenomenological interviews and noted that in these interviews, the interviewer's role is to help the participants to clarify their experiences [Hyncer 1985]. He argued that phenomenological interviewing is a difficult process which cannot be achieved without good interview questions. These interview questions play a significant role in encouraging the participants to delve deeper into their experiences and describe those experiences as fully as they can. In relation to the interview questions in phenomenological interviews, King has argued that a small number of open ended questions ideally can provide the participant plenty of time to elaborate on their experiences [King 1998]. King also argued that although the open ended interview questions allow the data to emerge, there is also a danger of collecting long descriptions of mechanical actions and even opinions from the participants instead of their experiences of a particular phenomenon. He has commented that the researcher although cannot avoid such descriptions using open ended questions, he/she should indeed engage these descriptions further to reach close to the phenomenon of interest and ask probing questions to motivate the participants explain their experiences of the phenomenon of interest [King 1998]. Koch argued that the openness of interview questions in a phenomenological interview is critical but one may also include a few direct questions [Koch 1996]. He explained that these direct questions can ensure the interview process to stay as close to the lived experiences as possible.

The aim of phenomenological interviews is to collect deeper and richer descriptions of the experiences of the phenomenon as lived in by the individual participants. Therefore, it is necessary for the interviewer to maintain integrity for the 'person centred approach' during the interviews. Koch suggested that the interviewer can achieve this by asking the right probing questions such as 'what happened then?' and 'what did you do then?'. He argued that such questions encourage the participants to describe their experiences at first place instead of their opinions, suggestions or views about something [Koch 1996]. Hyncer also stated that the interviewer has to ensure if the selected research participants have the ability to articulate their experiences [Hyncer 1985]. He mentioned a concern that the lack of articulating skills of the participant can keep the researcher away from investigating the phenomenon in a deep manner.

4.3.2 Decision trails- research data collection

With knowledge of the strengths and limitations of interviews, as a specific method of data collection under consideration, I was also interested to learn about it further from the researchers who have applied it in their research. I had many discussions about structuring interviews with my colleagues who were following similar research studies and I requested them to share their experiences of interviews and working with hermeneutic phenomenology. These discussions brought to my attention that 'living in the process and reflecting on it all the time' can guide the research process. From these discussions, I understood the importance of reflecting on my own experiences at every stage in the research. I considered narrating them in the thesis as the 'decision trails' to justify my decisions while shaping data collection and analysis process. While shaping data collection methods, my experiences as a postgraduate researcher and as an interview participant within a hermeneutic phenomenological study were particularly relevant. I revisited many events in my own journey as a postgraduate researcher, particularly when I was working on the research method, data collection and analysis. The data collection and analysis method was also driven by the research data itself, as I reviewed the data from the pilot interviews, and applied my reflections on the pilot interview process to structure the final interview method. I discuss some of these decision trails here.

Interviewing- a lived experience!

As I knew from the literature that the interview questions and structure are central to the hermeneutic phenomenological study, I decided to start writing the interview questions with the help of one of my colleagues who had some experience in phenomenological interviewing. I prepared two broad interview questions from my knowledge of literature before meeting him. I explained the research context and discussed the interview questions with him. He emphasized that while conducting these interviews, I should always consider the 'language that participants understand and speak' and keep the questions as simple as possible. I had his remark in mind, when I conducted my very first pilot interview. During this interview I asked the participant 'Can you walk me through your journey as a researcher in the nanoscience area?' Although the participant replied to it, I observed that he initially struggled to understand what I meant by that question. I received a short answer from him in response and he remained quiet waiting for my next question. I was expecting that the participant would share stories about experiments, meetings, conferences or something similar. So I was planning to note the important aspects he mentioned and probe them further in the flow of the conversation. On the contrary, I could spot the participant's struggle in understanding what I wanted to ascertain by that question. I then requested him to explain his research project and he responded to me with more ease. I followed his conversation carefully and later asked him about the easy/difficult parts and challenges he experienced in achieving his research objectives. I also requested him to share examples of how he discussed his work with others in the group. Before starting the interview, I wanted to keep it open ended, allowing the participants to bring up the issues that were important to them in researching in the nanoscience area rather than me defining the areas that I was interested to cover in this study. However, I realised that my broad (or open) interview questions were challenging to understand for the participants with a scientific or engineering background and perhaps sounded too philosophical for them to fully understand.

When I went back and listened to the audio recording, I understood why my colleague was suggesting about considering the ‘language that participants understand and speak’. I noted that the interview was more relaxing for the researcher when I asked him few direct questions about his research objectives and plan of research. It seemed to bring him in his comfort zone as he was familiar with such kind of wording. Later, when he opened up about some of the challenges in planning his research, I probed that dialogue further by asking a few ‘why’ questions. His response to my probing questions did bring a lot of experiential dialogue later on which I was keen to examine further in the analysis process.

Revisiting my experience of the pilot interview and reflecting on it, I understood what my colleague meant by ‘considering the language that the participant speaks or understands’. Continuously reflecting on the research process, I realized that semi-structured interviews had a better scope for data collection from postgraduate researchers. This thought process initiated the modifications to my interview approach from open ended to semi-structured, with a few predefined direct interview questions. Although I elaborated on the idea of ‘direct questions’ and ‘semi-structured interviews’ in the following decision trail further, I would emphasize here that such semi-structuredness of the interviews was not promoting pre-organized, or a start to finish plan of the interview. It was simply encouraging a more relaxed environment for postgraduate researchers to open up about their challenges, strategies, planning, efforts and feelings. Providing some basic prior information of what I was interested in through this enquiry ensured it minimized the experimental details and focused on the experiential content.

Participant feedback

Langdridge discussed that the participants' feedback can improve the rigour of hermeneutic phenomenological research analysis [Langridge 2007]. In my project I interviewed postgraduate researchers at different stages (first to fourth year) of their PhD. It was difficult to reach all the participants to obtain feedback on their transcripts' analysis in the limited time frame as a few participants had completed their PhD studies by then. However, I could reach the participants of the pilot interviews for their feedback as they were more easily accessible to me. After transcribing the interview and deriving the themes, I took the transcript back to the participants to receive their feedback on the interview transcripts and analysis. While most of them agreed with the themes, one of the participant mentioned that he could have discussed a lot more aspects of planning research, but at the time of interview he could think of only a few which were fresh in his mind. His comment brought to my attention that the interviews could be better if I could provide a few direct interview questions to the participants in advance. It will encourage them to think of their experiences of nanoscience research. So I started thinking about the questions. It took me back to an event called 'speed dating' in our institute organized for summer students by the researchers. In the speed dating, one member of each group interacted with a summer intern and described his/her research, research group and how he/she finds working on their project. I recollected my memories of that event and thought about how the researchers were describing their project, research group and work experience in general and gathered a few common aspects of those discussions. I then structured a few direct questions in which work experience in any experimental research area could be explained. These questions were the following.

- What are the objectives of your research?
- How do you plan your research?
- How do you explain your research to others?
- What are the difficult parts in your work?

By providing these questions, I simply wanted to direct the participants towards their experiences of nanoscience research and let them think about it before the interview. I also thought that since these questions reflect its person centric (specific to the person being interviewed) character, it would make clear my intention of collecting actual or lived experiences of working in the nanoscience area to them. Providing these questions beforehand, although I was a bit concerned that the participants may bring up their opinions or just describe their research technically, I was prepared for it. When such opinions were mentioned in the interview, I decided to request the participants to clarify further why they think so. If the opinions were based on their experiences then that was considered as a reflection of the participant during the interview process, and it would be phenomenological data.

In summary, the participants' feedback evolved the interview method. My own lived experiences navigated the interview questions and my reflections on the interview process guided data collection.

My experience as a participant

About three years ago, a colleague doing phenomenological research in the education area invited me to become a participant for his pilot interviews. He was interviewing me to understand my experiences of ‘being a researcher in the education research area’. As I was also conducting phenomenological interviews in my PhD research, I thought that this interview would be a good experience to live the life of the interview participant and discover the interview process from their point of view. I was also keen to know the procedural or methodological details of the interview process. Being a participant, it was difficult to keep note of reflections during the interview, therefore, I requested my colleague to provide me with the audio recording of the interview.

Before appearing for the interview, I had a dilemma in my mind. I was a novice in this research area and was struggling to understand the philosophical and methodological paradigms of the hermeneutic phenomenological methodology to decide if I could apply it for my research. Somewhere deep in my mind, I had a concern that my colleague was more experienced than me in this area, and my struggle with the methodology may appear trivial to him. I was also thinking that my interview will create an impression of me as a researcher on him which he will carry forward whenever we meet again. Therefore, during the interview, I mentioned very little about my methodological struggle. My colleague listened to me carefully and perhaps he noticed my hesitation. He then in the flow of conversation described his own struggle with the methodology and a few other challenges in his research to me. He described an account of how he felt in that phase when he was writing the philosophical underpinnings of his own research. I could feel that his involvement in my story was genuine. Our conversation led me to reflect on my research and evoked many other associated incidences as I shared my stories with him.

Being interviewed was a different experience for me and I noticed that my colleague was continuously trying to bring an ease and empathy to the process. He was asking probing questions to me at many situations which made me to reflect on my own experience. When I revisited the interview, I felt that by sharing his stories he made me realize that he is also a PhD researcher who faced similar problems. I could relate my feelings as an interviewee to my research participants, particularly those in the beginning stage (first year) of their postgraduate research. Therefore, I decided to spend a little time before each interview to foster similar atmosphere as that created by my colleague when he was interviewing me. I assured postgraduate researchers that I was not there to judge or analyse their performance as a researcher, instead, I was interested in their stories to understand how the researchers willing to work in nanoscience area can benefit from their experiences. I also iterated the ethical considerations before the interview and explained how the confidentiality of the data will be maintained in the research. I took effort to make the participant feel connected to me by sharing my own experiences as a postgraduate researcher occasionally.

Evolving the 'selective bracketing' approach

Van Manen stated that 'bracketing is almost unachievable in the examination of lived experiences' [van Manen 1997]. The 'selective bracketing' approach discussed in the thesis is the 'selective bracketing' of any possible influence of my views or ideas during the data collection (interview) process to avoid the navigation of the interview towards any desired outcomes. I have a clear knowledge of philosophical underpinnings of hermeneutic phenomenological approach and I bear complete integrity with those. The 'selective bracketing' was just an approach applied during data collection to collect more experiential data.

Selective bracketing of my views on disciplinarity during research data collection process evolved as a result of reflective recollections. Two events triggered the 'selective bracketing' approach. A few months after my interview (as a participant), I met my colleague who interviewed me for his phenomenological research and in our conversation he mentioned that many of my stories (which I described during the interview) were resonant with his own stories as a researcher in the education area, but he always allowed me to speak first in the interview. He said that he was careful not to prejudice my thinking with his experiences. He commented that 'I selectively bracketed my problems and challenges till you spoke about them'. The concept of 'selective bracketing' evolved as a combination of my reflection on that discussion and my literature readings. In my interviews, I was willing to share stories where relevant but with a care that those did not influence the researchers while articulating their experiences.

In a previous role, I had experience of working in an experimental physics lab where I was dealing with biological samples. If I recalled my 'day to day' activities in the lab, it was always about understanding physics with a biological specimen, no matter whether the research then was categorized with any labels as 'interdisciplinary' or 'multidisciplinary'! From my experience it was clear that exploring postgraduate researchers' 'day to day activities' will allow me to understand how they actually perceived and conducted nanoscience research. Further, if the complexity of disciplinary integration in nanoscience research really bothered the researchers? And, if yes, then how did they deal with it? I decided to selectively bracket my question 'if the complexity in disciplinarity of nanoscience bother the researchers?' until the researchers themselves speak about it. Kaplan et al. in their research investigating the practices associated with co-ordinating nanoscience research across the disciplines stressed the importance of investigating 'day to day' activities of postgraduate researchers [Kaplan 2012]. Reflecting on my experiences and reviewing the literature, I was confident that a focus on 'day to day' activities will bring forward the researchers' problems, challenges, efforts and learning in practice. Although I decided to focus on researchers' daily research activities, I was not intentionally leading them to explain the disciplinarity associated with their research in nanoscience research. I was instead considering that such understanding will emerge from their experiences.

4.3.3 Shaping data collection method

In summary, the semi-structured interviews have been evolved in this hermeneutic phenomenological research and the literature, my own experiences and recollected reflections guided the shaping.

These semi-structured interviews involved the following direct questions.

- Can you please describe your research project in detail to me?
- What are the most interesting parts of your research?
- Can you describe the good and bad parts of your project? Can you give some examples?
- What do you enjoy in your research?
- Can you please tell me about how you discuss your work?
- Which parts of your previous education were helpful in your current research?
- Would you call your research 'successful'?

The questions were emailed to postgraduate researchers prior to the interview. I started the interview session with my brief introduction followed by some informal conversation about my research work, any conference or workshop I attended recently. It sometimes encouraged researchers to share any similar stories they had experienced. I assured the participants about the confidentiality of the data at the beginning of the interview so as to encourage their involvement in the interview process. The interviews were conducted in a quiet meeting room to achieve good sound quality in the recordings. The interview timing was decided by the researcher and the interviews were conducted at his/her workplace. The interview duration was approximately one hour. I also maintained a gap of at least one week so that I could review the recorded interviews and reflect on what transpired from previous interviews.

Although I provided a list of interview questions, these questions were simply to encourage the researchers' to think about their experiences. In almost all the interviews, I started with the first broad question and followed the flow of conversation. Therefore, I did not maintain the same order of the questions to maintain a continuity of the researcher's thought process. However, I did a quick check that all the questions were discussed directly or indirectly before closing the interview session. I used probing questions such as 'what do you mean by that?', or 'what did you do then?' to keep the interview as close as possible to the researchers' experiences and minimising their views or opinions as suggested by Koch [Koch 1996]. If there were opinions emerging from the dialogue, I requested further explanation and/or examples from their work to support their statements. It was necessary to verify if such statements were pure opinions or had any phenomenological importance. At the end, I also encouraged the participants to describe any other part of their research experience which they thought I did not cover. The interviews were audio recorded and transcribed later and the transcripts were taken back to the participants if any clarification was required.

4.4 What constituted the research data?

In this section I discuss what constituted the research data. I divided the research data into two categories; primary research data and main research data. The interview tapes and written transcripts were considered as the primary research data. The interview transcripts were extensive so I decided to extract relevant contents to construct the 'crafted stories' (explained later in this section) for the hermeneutic phenomenological examination. These crafted stories served as the main research data.

According to Langridge, in a phenomenological research, the researcher must listen to the stories the participants tell of their experience and the events they describe as it is the first orientation towards the lived experiences of the participants [Langridge 2007]. My exploration was not just about collecting and describing the experiences, I was interested in understanding 'how postgraduate researchers' perceived this area and made sense of their work?' Therefore, these stories of postgraduate researchers' experiences were examined further with an interpretive rigor. I applied the hermeneutic phenomenological interpretive method for the data analysis. Postgraduate researchers shared many events or stories associated with how they developed interest in nanoscience research, how they were planning their research activities, how they approached new knowledge, theories and skills of other disciplines, how they discussed their research with others, what they thought was challenging and many more. They described different aspects of their research including reading, writing, planning, discussions, actions and challenges by telling a variety of associated events and stories. My probing questions illuminated the 'how, what and when' of these aspects but I was equally interested in knowing the ‘why’ of the acts associated with these aspects. This was possible by understanding ‘what was going on in their mind’ and not just by collecting participants’ opinions entirely from the straight forward questions. These stories and events were an ensemble of their feelings, ideas, assumptions, perceptions, opinions and actions.

4.4.1 Construction of the ‘crafted stories’

After reading each transcript several times, I extracted the sections highlighting the stories and events from each transcript. There were many stories which had associations with the phenomenon of interest, while a few, although were good examples of lived experiences, were not of particular relevance within the context of research. I carefully selected stories and events in relevance with the phenomenon of interest and began crafting these stories and events for the analysis. While crafting the stories, I removed expressions such as “emmm”, “I mean”, “actually” and the repetitive statements. I changed the names of personnel mentioned in the stories to maintain anonymity and coded the nanomaterial/sample/technique if the researcher expressed to maintain a confidentiality about it. The probing questions during the interview were aimed at collecting more in depth and rich description or ‘how, when and why’ of that lived experience. Once that was achieved and since I was interested only in those descriptions for further analysis, I removed the probes and kept the story continuous as if described by the participant as a whole. In this way the interviewee was the author of the entire story. There were a few statements or sections about the technical details of experimentation. While crafting the stories, I removed such statements if they were not adding any information to answer the research question. I had also maintained a diary during the interviews to note key words when the researchers were speaking about a particular aspect of his research or were stressing on something in particular. I revisited the stories to check if that part of the transcript was covered in the story. That way I could minimize my personal influence on the story selection and the process would give a voice to what postgraduate researchers thought important in that experience. At the end, each crafted story was labelled with a title derived by the holistic reading approach suggested by van Manen. A short descriptive summary of each story was also provided. These crafted stories constituted the main research data for hermeneutic interpretive analysis. After compiling the crafted stories, each transcript was also presented as a set of such crafted stories and a summary of each participant was constructed on the basis of these crafted stories. An example of crafted story titled *'identifying self'* is shown below.

Identifying self

When I started project, I was not interested in CCCC particularly but I was interested in coatings and nano materials in general. My senior Ross was working on CCCC. He suggested me to start with CCCC as he could show me how to use different characterisation tools with his samples. I was using this chance to learn about new nano materials as much as I can but I had no idea which material I am going to use. Sometimes, I thought that I would get carried away with CCCC which I may not be using but I had a trust on Ross that he will guide me well. I learnt how to characterise CCCC with different tools like Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM). With that practice, when I worked with my own samples, characterisation was pretty much the same. It turned out that the characterisation tools and processing technique for other materials was basically the same. CCCC happened to be just for the purpose, the purpose of learning. But, when I started with CCCC, I did not know that eventually I would work on same material. I was already using characterisation tools, in the first semester of PhD itself. So, it kind of kicked off and started my PhD straight away. It saved a lot of time. I was already using the tools AFM and SEM. Actually, I was introduced to them in the second year during the work placement, but then it was more theoretical. The work placement was of small duration so I could practise them. I was introduced to the physics of tools in the second year. In the final year project, I worked with some of the tools. Ross helped me in the lab when I started. So, in the hands on session, I could apply the knowledge from theory. I kind of had a good understanding and background of what the machine does. So, I didn't have to worry any more about learning them from the beginning. I did not have to invest extra time to think where to start my project. So, it got me started straight away and *made me to appear smarter than others. When I see other postgraduate researchers in the lab; or according to my progress so far, I feel I am ahead of them. I am already producing data and results, and these results are good for publication. I am about to start writing a paper and will be having a journal publication in the beginning of second year. It has not been done in my lab so far. It puts me at another level. I feel like doing much more. My supervisor last month asked me if I am interested in writing a student grant to take an undergraduate intern. It was a moment of pride for me, I felt that they trusts my capabilities now. It feels good that they expect such contribution from me.*

Summary: *In this story Alana described her experience of working in the lab in the first year and how she used the research material CCCC as a purpose of learning the characterization tools. Alana experienced a transition of her role as a novice researcher and a learner into a confident researcher in nanoscience.*

4.5 Data analysis process

Van Manen wrote that *'The method of phenomenology and hermeneutics is that there is no fixed method'* [van Manen 1997]. I would also argue that there are no specific steps for analyzing the crafted stories within the hermeneutic phenomenological interpretive methodology. Therefore, I experienced a dimension of freedom while shaping data collection method. However, at the same time, I was also keen to follow the guidelines and suggestions of many authors in shaping the data analysis process to avoid any criticism. Keeping a balance of both, I was curious to alter the data analysis method to give the best voice to the experiential research data.

4.5.1 Shaping the research data analysis process

The research data analysis process applied in this research has been structured on a few paradigmatic and/or methodological arguments about hermeneutic phenomenology discussed by different scholars in different research contexts at different times [Ajjawi and Higgs 2007; Lindseth and Norberg 2004; van Manen 1997; Whitehead 2004]. In particular, van Manen's work on hermeneutic phenomenology in education pedagogy [van Manen 1997] and Ajjawi and Higgs' work [Ajjawi and Higgs 2007] in medical practice influenced my analysis work. The analysis method blended thematic coding and hermeneutic circle analysis. Hermeneutic circle is central to the analysis. Also, deriving themes in the interpretive rigour is supported by van Manen’s notions of hermeneutic phenomenological analysis. Blending them in one method of analysis gives the best voice to the research data.

Van Manen M. recommended the processing of research data by exploring the thematic aspects of the data [van Manen 1997]. I based the themes construction on Ajjawi and Higgs’ explanation of the analytical steps/tasks in the phenomenological analysis. These steps are immersion, understanding and abstraction. After reading the crafted stories repetitively, I developed primary and higher order themes following analytical steps suggested by Ajjawi and Higgs [Ajjawi and Higgs 2007; Moustakas 1994]. In this process, the immersion and understanding involved developing the written research data, repetitive reading of the data and interpreting it to develop preliminary codes. Immersion in my research associated with developing the crafted stories and deriving primary themes, or preliminary codes as referred by Ajjawi and Higgs [Ajjawi and Higgs 2007]. These primary themes were close to postgraduate researchers’ own wordings (text). Van Manen suggested a ‘detailed reading approach’ similar to the immersion and understanding the process where researcher is required to concentrate on every transcribed sentence or cluster and ask ‘what is it revealing about the phenomenon?’ [van Manen 1997]. The abstraction step involved constructing the higher order themes which I associated with an interpretive rigor in my study. My own experiences as a postgraduate researcher, my understanding of the literature in this context and my continuous dialogue with the research data and primary themes were applied to derive the higher ordered themes. Van Manen discussed the primary and secondary themes as ‘explicit and implicit’ themes. Explicit themes were those which stood out more easily as important in the data analysis process while implicit themes appeared when the researcher dialogued with the text [van Manen 1997]. He discussed that the researcher can present the implicit themes to exhibit the readers 'what they are 'seeing' as meaning' thus pointing readers at interpretive meaning [van Manen 1997].

I was equally interested in analyzing the crafted stories as 'parts' and 'whole' by applying the hermeneutic analysis circle to the crafted stories. The hermeneutic circle involved three key processes - reading, reflective writing and interpretation [Laverty 2003]. The analytical steps of thematic coding are also grounded in the same key processes (reading, reflective writing and interpretation). Langdridge explained '*In the hermeneutic circle, the researcher moves, between part of the text and the whole of the text, to establish truth by discovering phenomena and interpreting them'* [Langridge 2007]. The whole of the text can be understood by understanding parts and the parts with reference to the whole [Smith and Osborn 2008]. Thereby, such moving between parts and whole of the research data is essential in the process of interpretation.

In the analysis, I was reading the crafted stories independently to explore 'what was the story about?', 'what particular aspect/s of nanoscience research were these stories revealing and finally to understand how a postgraduate researcher dealt with that aspect in his/her research. The stories were not linear nor were they focused only on one particular aspect each time. Hence, there was lot of moving back and forth in time. The postgraduate researchers were introducing me to different challenges they have experienced in different time frames, the people involved in different incidence or events, and how they dealt with the research in that situation. There was a lot of inter-linking or 'tying-off' or connection between the stories. Therefore, to understand the stories it required a lot of moving between parts of it to the whole of it. The hermeneutic circle was appropriate to make sense of the stories of each participant by going back and forth several times. I was also reviewing all of the crafted stories together to understand how different aspects of nanoscience research were experienced by different postgraduate researchers. Individual crafted stories and their ensemble were intertwined in the meaning making process. Therefore, I had to explore and understand parts as well as the whole of the stories to understand the phenomenon of 'researching in the nanoscience area?' Gadamer's concept of expanding the 'horizon of understanding' also fell into place when I was re-examining the stories by going back and forth in the research text in light of the previous interpretation.

Van Manen discussed that the researcher should be aware of the parts and the whole [van Manen 1997]. Going back and forth between the crafted stories of individual researchers, as well as, considering all the crafted stories as a whole, continuously reflecting on the research questions and research data formed a different level of understanding, and thereby one can understand the same phenomenon in a new way. In the analysis, each time with a new query in mind, I was applying the hermeneutic circle of analysis to all the crafted stories to see what I understood about it from individual stories and from whole of those. I reviewed the knowledge collectively to recognize what it adds further to my understanding of the phenomenon. Lastly, Van Manen also suggested a 'holistic reading' approach by which the researcher can capture notable phrases in the whole transcript text and use these themes as a framework around which the research data analysis work can be presented/explained [van Manen 1997]. I applied this approach while reviewing interpretive writing and themes collectively through a window of particular aspects and derived holistic or summative themes. I then structured the interpretive analysis work around these holistic themes. As suggested by van Manen, writing and re-writing continue in the hermeneutic circle towards newer understanding [van Manen 1997]. Theoretically, the hermeneutic circle can go endlessly and therefore the researcher needs to decide where to stop the process of interpretation and be satisfied with the understanding gained [Laverty 2003]. The researcher can present the newer understanding in the form of essential or core themes and comprehensively describe the core themes. This is referred as explication [Ajjawi and Higgs 2007; Moustakas 1994].

4.5.2 Decision trails- research data analysis process

Last but not the least, my own experience as a postgraduate researcher and my reflective association with the research process also had a purpose in this hermeneutic phenomenological research. My deep engagement with the research and my experiences guided the process of shaping the research data analysis method. I included some decision trails to explain this argument.

Sharing and comparing

Van Manen stated that "In phenomenology, the experiences common to the researcher and the research participants can be used to analyze what is most common, most familiar and most self-evident to the researcher" [van Manen 1997]. I applied this perspective on two occasions, while collecting the data by 'sharing' and in the data analysis process by 'comparing'. By sharing similar experiences with the postgraduate researchers in the interview I could create an empathy with the participants. The participants were excited by the idea that I took great interest in their particular stories and that I was able to understand what they meant. For instance, when one postgraduate researcher described his experience of review process of his paper asked me about my experience of review. He discussed that the reviewer of his paper was perhaps from a different discipline and therefore was suggesting more inputs in the methodology section of paper. In the conversation, he asked me about the review process of my paper and asked me 'what did you do in that situation?' I shared a similar experience with him and talked about my conversation with my mentor regarding it. In response to my story, the participant shared his own experience which was different than mine however sharing my experience evoked his response. Such sharing also provided the research participant with an opportunity to reflect further on his own experience. However, it was equally important to hold back my stories in the interview process unless the researchers spoke about any shared/similar experience first. I shared stories only when I felt that there is a greater scope of getting richer descriptions of experiences without breaking their line of thoughts. Such 'sharing' was only for creating empathy and not for disregarding or detaching the researchers from their life worlds.

The 'comparing' of experiences was particularly relevant when analysing what the new understanding emerging from the interpretive analysis process was offering to address the research questions. Being a postgraduate researcher myself, I tried to understand my own research area and was learning new research skills. Although my research context was different than my participants, we all were postgraduate researchers. I was able to situate the 'comparing' of experiences perspective to identify what attributes were specific or even unique to the nanoscience area. For instance, writing the first research publication was challenging for many postgraduate researchers including me. However, the challenge was mainly experienced due to a different style of writing for a research paper. The lived experiences in this realm were interesting but were not necessarily specific to nanoscience research in all the cases.

Living with the data and interpretation all the time

While I transcribed the data and listened to the audio files, I almost re-lived the interviews with the participants. I spent a considerable amount of time in reading and re-reading the interview transcripts and listening to the audio files during the analysis. I was involved in the interviews to such an extent that I felt that the written transcripts are in a conversational relationship with me all the time. I was continuously thinking about these stories, sometimes without even realizing about it. These stories occupied my mind when I was travelling, gardening, watching television and sometimes even during sleep. Many themes (secondary) resulted as an output of my concentrated involvement with these stories with a pen in hand. A few themes were a result of my subconscious mind thinking continuously about what themes were emerging from these stories and at times they have flashed as my intuitions.

A few stories of the participants revealing their perspectives of approaching their research in the nanoscience area were so inspiring that, as a postgraduate researcher and as a teacher, I was motivated by those stories personally. It would not be wrong to say that the research participants influenced my own way of working as a postgraduate researcher and a teacher. As Giles argued "*Phenomenological research is itself a lived experience for the researcher"* [Giles 2008].

I was keen to present the crafted stories and analysis to my supervisors and colleagues during the supervisory meetings. I wanted to get their feedback on the analysis. In the interpretive analysis, I considered it as a way to judge if my personal bias influenced the data analysis. I received great encouragement to present the analysis work in writing and discuss my thoughts during the analysis. There were times when phenomenological interpretive writing was a struggle but such exercise of writing turned as great practice to engage with the research data and judge the rigour of the research process.

4.6 Ethical considerations

Since the research dealt with human subjects (postgraduate researchers), ethical considerations were important in this study [Kvale 1996]. The research ethics committee of Dublin Institute of Technology (DIT) has its own codes and conducts of ethics which are guided by commonly agreed standards of good practice as laid down in the declaration of Helsinki and European Science Foundation. The DIT research ethics committee examined ethics application and granted ethics clearance for this research in July 2010. In my application to DIT research ethics committee, I discussed the research questions, potential participants involved in the research, participants' selection processes, data collection and analysis method and complete research schedule. I also discussed how the anonymity and confidentiality of participants' identity will be achieved and how the research data will be protected during and after the completion of research. For example, given the nature of the hermeneutic phenomenological interviews and context of the research, it was anticipated that the postgraduate researchers will share the information about their research work, research group, colleagues, institute and collaborators during the interview. Therefore, I discussed how any identifying material in the interview will be coded for further use. During this research span, all audio recorded interview tapes of the interview were converted into written transcripts and these transcripts were used for the analysis purpose. In the written transcripts, all identifying material including names of participants, institution, research group and collaborators was coded. I also allocated codes if the researchers did not want to disclose any particular research technique or component. The audio files and the written transcripts were stored securely in my personal computer at the institute.

I considered the confidentiality of the research data at all the times during the research process. Any reproduced material based on the research data such as research publications, presentations and thesis followed the pseudo names or codes allocated in the written transcripts and no references were subsequently made to the original version that was coded.

I provided the information about the research process, confidentiality of the research data and withdrawal policy to the postgraduate researchers before the interview. They were provided with my contact details if they needed any further information about my research or about the security of the research data. The participants were also informed that they had a right to withdraw from the study at any stage if they chose to do so. Providing the ethics information enabled the postgraduate researchers to participate in the interview fully aware of what was involved. I was well aware of ethical considerations to be made in this qualitative research and have maintained my integrity for ethics throughout in this study.

4.7 Maintaining qualitative rigour and trustworthiness of the data

This research is conducted with a qualitative approach. Although a qualitative approach is well supported in education research, it is important to demonstrate how rigour and trustworthiness were achieved in the research process. The pressure to demonstrate the rigour and trustworthiness of the data is more when hermeneutic interpretive phenomenological research is applied as the researcher brings their own reflections and experiences to the process [King 2011].

Van Manen suggested that the rigour in research with a hermeneutic phenomenological methodology can be judged on four criteria; orientation, strength, richness and depth [King 2011]. Orientation is about the involvement of the researcher is the participants' stories with a focus on the research questions. In this study, my orientation was on my research questions when I examined postgraduate researchers' experiences. In the whole research process, I was so deeply involved in the researchers' stories that I relived each moment with them. Richness is about the richness or detailing in the text that narrates the meaning as perceived by the participants, while depth is about the strength of the text to portray the meaning of the phenomenon. Being a postgraduate researcher myself, I could empathise with the researchers during the interview. Sharing my own experiences and asking questions and providing examples enabled the participants to describe their experiences of nanoscience research as fully as possible. Further, with my writing skills I was confident that I could describe and interpret their experiences and thereby discuss the meaning of phenomenon of researching in nanoscience area in its fullest richness and greatest possible depth.

Koch recommended including the decision trails as a part of good research practice to demonstrate the rigour in interpretive analysis research [Koch 1996]. By sharing the decision trails, I made my readings, thoughts, reflections and experiences available to the reader and demonstrated how I had taken the 'strength' criteria suggested by van Manen into consideration. I had always been transparent about the data interpretation process and delivered the research outcomes to the education community to seek their comments or suggestions. The research was well received by teachers, researchers and education researchers. In addition, the research process was guided by their timely suggestions which gave an indication of the trustworthiness of the data.

By describing the decision trails, I discussed how specific research methods of data collection and analysis evolved as I was engaged more and more with the research. When I started making a note of my experiences and reflections in the data collection and analysis process, it made a lot easier to explain how I was living this research. Van Manen supported the process of 'talking and writing about the experiences' as a reflective awareness [van Manen 1997]. My intention in this research was to apply my own experiences and reflections to draw the conclusions from the interpretive analysis process, but having said that, I also wanted to keep the analysis process clear (transparent) so that whether my prejudices were overriding the research conclusions at any stage could be judged. My experiences 'as a postgraduate researcher' were not a research data in the literal sense, but they were applied to make a sense of the interpretive research data and derive an understanding of the phenomena from it. I refer to Heiddger's argument *"In interpretation, understanding does not become something different. It becomes itself!"* [Laverty 2003].

4.9 Summary

In this chapter I described the data collection and analysis method applied in this research. As discussed, the particular method of data collection and analysis evolved as I turned to the phenomenon of researching in nanoscience area, in the postgraduate researchers' stories, in my own stories, and in the literature. I presented a few decision trails to explain the journey of reshaping the research data collection and analysis method. I also presented an example of a crafted story. Being transparent about the research process, also, discussing the biases/prejudices, I invite the reader to scrutinise the data analysis discussed in the following two chapters.

Chapter 5 Research data analysis

5.1 Introduction

The research in the thesis is guided by van Manen's ideas of hermeneutic interpretive phenomenology [Laverty 2003; van Manen 1997]. In particular, Heidegger's and van Manen's ideas of the hermeneutic interpretive analysis circle, Gadamer's notion of 'fusion of horizon' and Ajjawi and Higges's explanation of the analytical steps in thematic coding guided the research data analysis process [Ajjawi and Higgs 2007; Gadamer (1975/reprint 1996).; Laverty 2003; van Manen 1997]. Further, I applied a 'holistic reading' approach suggested by van Manen [van Manen 1997] in order to derive notable phrases and broader/summative themes by reviewing the research data. These holistic themes were applied to present the hermeneutic interpretive analysis work in a systematic manner for the readers.

This chapter provides a step-by-step account of the research data analysis. In the first section (5.2), I describe an example of the analysis of an individual postgraduate researcher's transcript. It involved the analysis of the individual crafted story as well as the analysis of all the crafted stories (together) of that postgraduate researcher. A summary of the transcript analysis was then developed. The process was repeated for each transcript. There was a lot of 'tying-off' or connections between the crafted stories of each individual researcher. Therefore, to understand the experiences of an individual postgraduate researcher, a lot of moving forwards and backwards in the hermeneutic circle within the story, as well as, between the crafted stories of each postgraduate researcher was required. The second section (5.3) discusses the analysis work carried out by considering all the crafted stories and summary of participants together and reviewing these stories as 'parts' and 'whole' in the hermeneutic analysis circle. Therefore, in a literal sense, I applied the hermeneutic analysis circle in two phases, firstly while analysing the individual researcher's crafted stories and secondly during the analysis of all the crafted stories together.

In the first few readings of the crafted stories, I could identify a few lived experiences that were common to some of the postgraduate researchers, while some lived experiences were unique to individual postgraduate researchers. One possibility of such commonness could be the very nature of postgraduate research in general, and that, the identified lived experiences were about 'being a postgraduate researcher' in general. In that case, I wanted to examine further if these lived experiences were specifically about nanoscience. I did this by comparing these experiences occasionally with my own lived experiences as a postgraduate researcher. Van Manen's suggestion of using researcher's own experience as a starting point guided this process [van Manen 1997]. Another possible reason for the commonness of a few lived experiences may have been situated in the nature of nanoscience research, i.e. some particular aspect of it experienced in a similar way. The commonness (or similarities) of the lived experiences identified during the interpretive analysis is presented clearly where relevant; however, it did not lead to any intentional generalisation of the research findings by eliminating (or neglecting) other lived experiences in the similar context. Each postgraduate researcher therefore contributed to this journey of exploration of lived experiences. While discussing the analysis in section 5.3, I grouped together the lived experiences under similar contexts and discussed their commonness (and/or uniqueness). This allowed a deeper understanding of that particular aspect of nanoscience.

One feature of the hermeneutic phenomenological analysis is going back to the research questions with a newer understanding of phenomena [van Manen 1997]. Examining researchers' lived experiences allowed deriving the essential or central meanings of the phenomenon 'researching in nanoscience area' and thereby understand the phenomenon newly. With the new understanding of the phenomenon, I approached the research questions related to the disciplinarity, knowledge, skills and competences associated with nanoscience research area with a new vision and confidence. The summary of the research data analysis of this hermeneutic phenomenological examination is a tureen of the essential meanings of the lived experiences which provides a newer understanding of the phenomena. While this chapter discusses the primary, secondary and holistic themes and the interpretive analysis; the following chapter (chapter 6) presents the essential meaning of the phenomena derived from the further interpretation of research data analysis. Furthermore, what this new understanding of the phenomena has offered to address the research questions is discussed in chapter 7.

The interpretive analysis resulted in a number of recommendations/guidelines for curriculum development in nanoscience which are discussed in the following two chapters. Some of the recommendations were articulated by the researchers themselves while the remaining ones emerged from my interpretation of the research data. The recommendations articulated by the participants were included only after confirming their phenomenological nature. They were identified as postgraduate researchers' reflections on their lived experiences in the analysis process and not just as straightforward opinions. In the reminder of this thesis I write the term 'lived experience' as 'experience'.

5.2 Example of analysis of crafted story/ies and developing summary of transcript

This section is divided into two sub-sections. In the first sub-section (5.2.1), the example of analysis of an individual crafted story is discussed. The second sub-section (5.2.2) discusses an example of the analysis of the individual researcher's transcript, considering together all the crafted stories constructed from that transcript. At the end of the interpretive analysis of the individual researchers' transcript, a summary of the individual researcher is presented (example shown in section 5.3). The process is repeated to write the summary of each postgraduate researcher's transcript. Appendix 3 includes titles of crafted stories of all the research participants.

The analysis process is illustrated with Alan's transcript as an example. Five crafted stories obtained from Alan's transcript are listed below.

- Skill of simplification
- Building learning 'bottom to top'
- Adopting common vocabulary
- Disciplinary knowledge as building blocks
- Being there when needed

5.2.1 Analysis of individual crafted story

An example of the analysis of individual crafted story is shown in this section. The first crafted story 'skill of simplification' is analysed as an example. The primary and secondary themes derived from thematic coding are mentioned below the story.

Skill of simplification (Alan)

Our group is very interdisciplinary. We even have a biologist doing some antibody and antigen work. She had to write a section about preparation and testing of gratings in her paper in very simple terms for a biology journal. When I described to her the optical interference pattern, she didn't get it at all. So, I had to break it down. I explained to her the meaning of interference first, then how the interference pattern can be obtained from LASERs. That way she understood it more clearly. I told her to explain what she understood from our conversation, later I noticed that she had framed similar statements for the paper. Sometimes I have to explain my work to the group of people, not all physicists, some are from company and are interested in business and have little knowledge in physics. So, I use the same strategy to explain the research to them. It is the level that everybody can understand. They are intelligent in their own areas, so you are not diluting the research, but trying to simplify it so they can absorb industry relevant information from it. But, for slightly complicated concepts, I probably use the figures, as it can explain the concept in a lot simpler way. I noticed when working with these people, I try to simplify the things at the best for them.

Collaborating with people of different departments at the beginning was somewhat challenging. The biologist girl I mentioned about, she loves the acronyms. They use a lot of PCR (Polymerase chain reaction) and all related techniques, and they just talk that in code language all the time. When I started this structured PhD, I did an advanced analytical techniques course within first few months. One lab in that course was about NMR (Nuclear Magnetic Resonance). The instructor explained about the instrumentation in the beginning, and then asked us to do some chemistry associated with that. Now, the instructions about preparing solutions were so difficult to understand as I had no clue about what is PPM (part per million), molar concentrations etc. And she was flying through it. I was aware of what NMR is used for but the chemistry of solutions was hard. So, I had to tell her finally that I have no background of Chemistry and unable to pick these acronyms, I requested to simplify that for me. I know, she thought that was stupid initially, but then I explained her that I am not aware of the formulas, but, I know about how to make basic concentrations or dilutions. So, she simplified it for me. With the biology girl, we had to adapt to the level that we both understood each other. We need to be patient and point out when we require more explanation sometimes.

Themes: *break down explanation in parts, simplifying work according to the audiences, using diagrams/images for explanation, perception of boundaries, difficulty with acronyms, pointing out for more simplification/ explanation*

Description of the crafted story (skill of simplification: Alan)

In this story, Alan described his encounter with people from different disciplines on two different occasions. In the first, he was helping his colleague from biology to understand a physical science technique. He mentioned that he had to modify his style of explanation 'by breaking it into simple parts' such that his explanation is simplified and his colleague understood it better. He also confirmed the practicality of his style of explanation. He followed the similar style to present his work to the industry collaborators. On second occasion, during the laboratory training, Alan noticed that understanding the 'dialogue of people from other disciplines' was challenging in the beginning. It was due to not understanding the acronyms/terminologies used by researchers of other disciplines as a common practice. He had expressed that difficulty/challenge to the biology colleague/instructor and requested a more basic explanation to understand the acronyms correctly. He reflected that the challenge of acronyms and new terminologies would appear 'trivial', 'stupid' or 'not so serious' from the point of view of other disciplines. He further commented that the researchers can deal with this challenge by 'being patient and requesting more explanations' and by maintaining a 'common level' for explanation such that everybody can understand it.

Interpretation of crafted story (skill of simplification: Alan)

Initially, both the occasions when Alan had to deal with researchers from other disciplines were narrated by him without much elaboration, however when probed further, he discussed many examples during the interview which resonated with these lived experiences. Therefore, it became necessary to dwell back and forth between the stories within the transcript in order to understand the meaning of these lived experiences (in the presented crafted story). From the holistic reading, two broad themes were captured from the crafted story for further exploration: ‘communicating with people from other disciplines’ and ‘understanding language of other disciplines’.

Alan’s statement *‘we need to be patient and point out when we require more explanation’* at first appeared as an opinion. When I iteratively reviewed the story applying hermeneutic analysis circle, each time searching ‘what has happened’, ‘why did he say that?’ and ‘what did he do then?’, I could detect the phenomenological richness in his reflection. In the training programme in the first year of a structured PhD, Alan had experienced challenges in adopting new or different acronyms from other disciplines (chemistry and biology). His description of the challenges informed the ‘what’ question. He was aware that this challenge may not appear serious to the other researchers/trainers. His comment ‘she thought it was stupid’ conveyed his thoughts. To continue the training programme, it was important for Alan to understand these acronyms and therefore his act of ‘requesting more detailed explanation’ appeared to me as ‘thoughtful’ and ‘intentional’. It answered the question ‘what did he do then?’

The statements *‘That way she (colleague from biology) understood it more clearly’* and *‘with the biology girl, we had to adapt to the level that we both understood each other’* were reflections of Alan about his act of practically explaining the concept of optical interference. His method of ‘simplifying the explanation in parts’ evolved after he noticed the difficulty his biology colleague had in understanding the physics concepts. Further, Alan verified this method of explanation by requesting her to describe her ‘achieved/gained’ understanding. He noticed that she was converting their informal discussions to formal and concrete reasoning. Considering all these events in the story, I interpreted that Alan considered the skill of ‘pointing out the need for explanation where necessary' important when dealing with the challenge of new terminologies/acronyms following his experience of working with colleagues from other disciplines. His perception that other research colleagues and industry collaborators may require simplified explanations could be a result of such consideration.

With this knowledge, I moved on to the other crafted stories knowing that I would return to this story with a better understanding of the broad themes derived from it.

5.2.2 Analysis of all crafted stories of individual researcher

The example of analysis of the individual researcher's transcript, considering together all the crafted stories constructed from that transcript is discussed in this section. All the crafted stories constructed from Alan's transcript are included in appendix 1 titled 'crafted stories from Alan's transcript'.

I began to explore the broad themes: 'communicating with people of other disciplines' and 'understanding language from other disciplines' by examining other crafted stories from Alan's transcript. At this point, I was equally interested in collecting newly emerging themes from other crafted stories as well as reviewing the crafted stories as 'parts' and 'the whole' to understand the meaning of Alan's lived experiences of nanoscience. In Alan's story 'skill of simplification', I could detect that Alan perceived distinct boundaries between different disciplines when he was learning and/or explaining something. For instance, he said:

> *'The biologist girl I mentioned about, she loves the acronyms. They use it all the time and they just talk that in code language all the time'.*

However, I had to ensure that my interpretation did not override what Alan was trying to say. When I examined other stories, these perceptions became clear. In the two crafted stories: 'adopting common vocabulary' and 'building learning: bottom to top' I understood how Alan perceived these boundaries strongly.

Alan described how he learnt knowledge of other disciplines in the stories 'adopting common vocabulary' and 'building learning: bottom to top'. When he was explaining his research to the undergraduate students, he was keen to start with the knowledge ('building blocks' as he refers them) that they were familiar with, and then, build the story around that to explain the complex terms. His method evolved as a reflection of his own 'experience of learning' quantum biology, where he learnt to connect physical laws of thermodynamics with biological processes in order to understand biology at quantum level. He situated the knowledge he was already familiar with as 'fundamental building blocks' to construct knowledge where he could develop 'connections between the blocks' and understood the concepts of quantum biology. His recommendation of constructing a platform of knowledge; with the 'known knowledge' as 'fundamental blocks' thus originated from his experience of learning quantum biology and from undergraduate teaching.

In the crafted story 'disciplinary knowledge as building blocks', Alan described his idea of 'building blocks' with a few examples. Alan was researching on coating the optical grating surface with XXX nanomaterials such that these coating could form a plane where antibodies can attach. He was applying techniques such as fluorescence testing to confirm the attachment of the antibodies/cells. When I requested him to explain how he achieved his research objectives and learnt the techniques involved in his research, he described his efforts of understanding the chemical and biological systems in the story 'disciplinary knowledge as building blocks'.

Alan referred to his disciplinary knowledge in physics as 'fundamental building blocks' which was a platform to construct new knowledge in his research. In other words, he emphasised the importance of his disciplinary knowledge when he set out to explore the new knowledge associated with the other disciplines. On another occasion, when Alan was learning basic cell culture techniques in a biology lab, he admitted that it was a new and altogether different procedure. He specified that he could not learn it by remembering the names or acronyms of the associated techniques, but, by remembering what its purpose was. He described his confusion with the words 'aliasing' and 'lysing' which sounded phonetically similar but have different meanings in biology and physics, and they were used in very different contexts by different disciplinary experts.

Reviewing all four stories with a holistic approach, I noticed Alan's inclination towards 'simple explanations' and a theme 'adaptation' emerging from all the stories. Alan was trying to convey that the other scientific disciplines can have their own methods of presenting knowledge, techniques and results. When he was trying to understand these methods, he was expecting an adaptation of 'simple or basic level explanation' or 'common vocabulary' that can be understood by all and can communicate knowledge in best possible ways between the disciplines. He described that the starting point of learning any new disciplinary knowledge can be realising their connection with the existing knowledge of their own discipline. I reached an interpretation that nanoscience researchers should be prepared to mention and simplify even seemingly minor steps, techniques or concepts to the researchers from other disciplines. Alan's crafted story 'being there when needed' added the additional element of 'trust' to this interpretation.

In his story ‘being there when needed’, Alan described how Siobhan (his colleague from the biology discipline) ‘being there’ relaxed him and made him to realise the simplicity of the protocol/standard test of another discipline about which he was initially confused. Being there and being accessible was of great importance for Alan. I could detect from Alan’s description that he trusted Siobhan’s knowledge of her discipline and therefore the interactions were valued and cherished by him. Another theme ‘trust building’ emerged from this interpretation which I decided to explore further. However, there were a few stories discussed by other participants in similar context but in more depth, and therefore I decided to discuss the theme later with a greater attention.

When I read all the crafted stories again, it was interesting that Alan described his challenges about acronyms and terminologies of other disciplines, while at the same time, in the interview he used acronyms and terminologies including UV (ultraviolet), AFM (Atomic Force Microscopy), LASER, TEM (Tunnelling Electron Microscopy), plasmon resonance, aliasing, diffraction pattern. I could understand these terminologies and acronyms because of my academic background of physics but when I selectively bracketed my earlier knowledge of these acronyms, I could grasp the intensity of this particular challenge. Alan probably assumed I had a physics background as I had met him earlier at a physics student conference.

5.2.3 Summary of Individual transcript

The summary of Alan’s transcript is given below.

Alan perceived boundaries from different disciplines while understanding the techniques or protocols of other disciplines and explaining his research to others. He believed that the challenge of understanding new acronyms/terminologies of the other disciplines did not appear serious from the lenses of the other disciplines. This was apparent when Alan was undertaking a practical workshop in the advanced analytical techniques, instructed by the researchers from a chemistry discipline. From that experience, he realized the importance of 'pointing out the need of explanation where necessary' and therefore advocated this skill. He commented on using 'a common vocabulary' in the research.

Alan reflected on his own experiences of learning quantum biology by building connections of thermodynamics laws with biology to explain the biological process at quantum scale. He applied a similar approach to understand the chemical and biological processes by exploring the physical aspect (what is happening physically) of the process first and then learning the biological explanation. Therefore, his disciplinary knowledge was the building block by which he approached new knowledge in other disciplines. His disciplinary knowledge was trusted by his colleagues. On another occasion, he trusted the knowledge of his colleague from the biology discipline. In short, he witnessed and/or encountered different knowledge worlds of other postgraduate/postdoctoral researchers occasionally in nanoscience research and his research work flourished by mutual trust and help offered by each other to delve in others knowledge worlds. He believed in 'tailoring the explanation at simple or basic level' while working with researchers from other disciplines. In a few of his lived experiences, 'verbal communication' was central to coordinate knowledge across the disciplinary boundaries. It also suggested that the researchers act as a 'resource' of exchanging knowledge of their discipline and therefore the inheriting quality of 'trusting others' and/or 'being trusted' in the knowledge exchange process is vital.

5.3 Analysis of crafted stories as a group

The understanding of nanoscience achieved from Alan's stories was the beginning of the interpretive analysis process. When I was analysing Alan's crafted stories, I had a previous understanding of the phenomenon coming from my own beliefs and assumptions. I allowed Alan's experiences to construct a new understanding of phenomenon and therefore influence my perspective. Gadamer explained this influence of the participant's standpoint as the 'fusion of horizon' notion [Giles 2008]. He suggested that when the researcher arrives at a point where he encounters the standpoint of the participant, he/she allows the participant's standpoint to influence his/her own views as a fusion of horizon. However, the researcher should be aware of his/her prejudices and views (together referred to as standpoint) for that and he/she should be in continuous conversation with the research data in hermeneutic circles to reach new understanding. My horizon of understanding expanded to include the experiences of other postgraduate researchers when I examined other crafted stories. With my dialogue with the crafted stories through reading, writing, dialoguing and fusion of horizon in hermeneutic circles a different level of understanding was achieved each time. While undertaking this analysis, I was aware about van Manen's writing that *"lived life is always more complex than any explication of meaning can reveal"* [van Manen 1997]. However, one can always hope to obtain some newer understanding of it when the research is pursued with great rigour.

In sections 5.3.1 to 5.3.6, the interpretive analysis carried out by considering all the crafted stories together in the hermeneutic analysis circles is described. Each section discussed the analysis of postgraduate researchers' lived experiences of nanoscience research, collected in a similar context. I included a few crafted stories discussed in each of these sections in appendix 2 (titled ‘crafted stories’) so that the reader can be equally engaged with the analysis process and experience the same level of enthusiasm as mine. However, the analysis involved a lot of going back and forth between all the crafted stories describing the similar context in the hermeneutic analysis circles and added layers of interpretation.

5.3.1 Same instruments different ‘knowledge worlds’

Nanoscience researchers make use of many nanoscale instruments and techniques in their experimentation. Reading all the crafted stories I learned that these nanoscale instruments and techniques were used for a range of different research purposes. For example, these facilitated the researchers to: i) characterise the nanoscale objects in terms of size and scale; ii) visualise the nanoscale assembly such as deposition layers; iii) observe bio-cellular interactions with nanoparticles; iv) scrutinise nanoscale devices in their process of development; v) measure physical properties and vi) observe lattice structure of samples. The researchers were introduced to some of the techniques in their undergraduate degree courses either theoretically, in practical sessions, during work placements, while other instruments and techniques were new in their postgraduate research. The researchers spent considerable time learning about and/or working with these instruments and interpreting the data obtained. Therefore, these instruments were essential objects of their life worlds as a researcher in the nanoscience area.

Although the nanoscale instruments were central to nanoscience research for research data collection I noticed varying perceptions of ‘learning the nanoscale instrumentation’. Some researchers considered ‘learning instruments’ as an important aspect in nanoscience research while others associated nanoscale instruments and techniques simply as ‘devices’ of research data collection. I included 3 crafted stories in the appendix 2 to discuss the themes and analysis in this context. The stories are the following:

- Not all instruments are central (Anna)
- AFM (Ronan)
- Identifying self (Alana)

In Anna's story 'not all instruments are central', it is evident that using AFM and SEM for obtaining the research data was part of her research work however these instrument were not seen as central or essential to her 'learning'. She perceived herself as a 'biologist' and had distinct boundaries in relation to which instruments/techniques she was interested in learning and others were considered as 'devices' for the purpose of research data collection. She simply adopted the results locally (collecting data with the help of technician) in her research.

In Ronan's story 'AFM', he explained how working on an AFM set-up was challenging due to its crucial settings. He commented that handling the AFM set-up was an achieved skill in this research, whereas, with TEM, he simply collected the research data. He perceived TEM as a 'data collection tool' as he did not operate the tool on his own.

In Alana's crafted story 'Identifying self', she explained that she could progress in her research at a faster pace due to an early exposure of theoretical knowledge of the nanoscale instruments, and working experience with AFM and SEM techniques during work placement. She received recognition from her supervisors. Ronan also expressed that the hands on experience of AFM and TEM in undergraduate laboratory courses would have been advantageous for him.

Reviewing the three stories holistically, I interpreted that all three researchers approached similar instruments and techniques with different intentions, prior knowledge, skills and prejudices and hence achieved a different levels of understanding of these instruments and techniques. Anna had a biochemistry background, Ronan had a physics undergraduate degree and Alana graduated with an engineering degree. Although, the AFM, SEM and TEM techniques were points of intersection (nexus) in their research and they were necessary in each of their studies, researchers' approaches to these techniques were very different, and hence, their level of engagement with these techniques varied. Therefore, although the nanoscale instruments were seen as a common link between the different disciplines, cognitively they were connected to the discrete/separate knowledge worlds of each postgraduate researcher. In that case, the portrayal of the entire nanoscience area as 'a unique discipline' with a common knowledge world around the nanoscale instruments seem to conflict the explored lived experiences.

It is equally true that these nanoscale instruments are at the nexus (at the intersection) for the disciplinary knowledge worlds. Following the understanding attained I described this link/intersection of nanoscale instruments with the knowledge worlds to be 'abstract' or 'superficial'. It is true because there were examples where postgraduate researchers perceived and experienced strong boundaries of disciplines resulting in constraints in the collaboration. The knowledge worlds of postgraduate researchers were separate or compartmentalized when they were dealing with the instrumentation. In such situations, there was little hope of improving the communication or other disciplinary views associated with the instruments. However, I also detected some examples where postgraduate researchers were trying to cross over the boundaries of their disciplines when dealing with nanoscale instruments and were making use of their own knowledge worlds, approaches and skills to understand knowledge worlds of others and understand nanoscience.

I chose different nanoscale instruments (than TEM and AFM) which were again widely used by the postgraduate researchers in nanoscience research. This would also give me a broader perspective of nanoscale instrumentation and associated knowledge worlds and I noticed that in some cases, researchers were reconstructing their own knowledge worlds with these instruments and techniques while working in collaboration with the researchers of their own discipline and carrying over the knowledge to research in other disciplines. Overall, nano scale instruments were giving the researchers an opportunity to connect to knowledge worlds at least at abstract level. I analysed other crafted stories in this context in hermeneutic circles and they expanded my horizon of understanding. I included three crafted stories to discuss the analysis. These crafted stories are following.

- Sharing and questioning information (Ciaran)
- Multiple disciplines at the instruments (Ruth)
- Sharing knowledge world (Michael)

Ciaran's experience of working with XPS data of his nanoscale coatings described how the 'sharing and questioning the knowledge about instruments' proved important in his research. Ciaran expected more cognitive depth or involvement was necessary in this research and experienced that such depth could be achieved by asking questions on the techniques applied in the research and understanding it. Ciaran had a physics background. While working with the analyst from chemistry, he took efforts to understand the analysis conducted by the analyst (from chemist's perspective) and verified if his research data was correctly interpreted by her. He raised a query about the technique and asked for more details of the XPS analysis from the analyst. He commented that questioning the technique could strengthen his knowledge in nanoscience.

Ruth's crafted story 'multiple disciplines at instruments' described a different lived experience. Ruth benefited greatly from the presence of research colleagues who shared their expert knowledge with her. Ruth worked in a large research cluster and shared many instruments during her PhD research with other researchers. These instruments were part of the central facility provided to the university. Although, most of the researchers associated with the big research cluster were using these instruments, their research objectives were different, making the central facility or equipment not necessarily central to their research. However, working with these instruments provided postgraduate researchers the opportunity to help each other in the area they were expert in and share their knowledge. It fostered a good atmosphere within which they could carry over the reconstructed knowledge to work with other disciplines.

Reviewing these stories holistically and comparing my previous understanding, I interpreted that in some cases, the instruments or common techniques can help to construct a bridge to the knowledge worlds of other researchers and allow the crossover of disciplinary boundaries in a few different ways. Ciaran's reflections suggested the importance of 'asking queries and more explanation' when researchers share a common research interest. Ruth's story described examples of how postgraduate researchers could build a strong lobby to make use of each other's expertise in the nanoscience area and thereby obtain at least the minimum understanding of other disciplines necessary for their own research. Ruth's story also described how the researchers took interest in others' projects associated through the central research facilities or instruments.

In Michael's story 'sharing knowledge world' he described cumulative efforts of his and his colleagues' work to standardize a protocol for the deposition of nanomaterial with low temperature plasma. His story described how the 'reconstruction' of mutual knowledge worlds was possible with continuous support from other researchers while working on similar instruments/techniques.

When all the crafted stories in this context were compared, it was clear that the postgraduate researchers approached nanoscale instruments with different intentions, knowledge and skills and hence achieved different levels of understanding of these instruments and techniques which cannot be generalised. However, it can be interpreted that the nanoscale instruments and techniques have initiated the connections between disciplines at abstract level. Some postgraduate researchers approached and occasionally strengthened these connections by exploring knowledge of other disciplines while some experienced resistance in the process. The strengthening of the disciplinary connections was achieved by boundary spanning efforts of the postgraduate researchers and the nanoscale instruments served as an abstract medium.

5.3.2 Publishing research: conflicts, authority, sense of responsibility and trust

The postgraduate researchers are often encouraged to disseminate their research findings through research publications in peer-reviewed journals and/or presentations at conferences, workshops and meetings. Publishing results in peer-reviewed journals is considered as one of the most important ways to get the research work recognised in the research community. Many researchers described their awareness, opinions, perceptions and interests about publishing research through academic and scientific journals. During the interviews, the researchers described different aspects of their experiences of writing research journals, including developing drafts, discussing and reconstructing these drafts through cycles of corrections, selecting appropriate journals for publishing research, the peer review process and many more. A few of these lived experiences were coherent or lived by many postgraduate researchers in similar ways. Being a postgraduate researcher I had similar experiences with my PhD. Although these experiences were a part of their 'being', I was more interested in those experiences related to their life worlds as a researcher in nanoscience area. My analysis focused on exploring if any of these experiences were specific to nanoscience. I described various aspects in the context of publishing research in the nanoscience area in this section. I included 3 crafted stories in the appendix 2 to discuss the themes and analysis in this context. The stories are the following:

- Transparency about publishing research (Sean)
- Judging work from lenses of other discipline (Ciaran)
- Sense of responsibility (Michael)

Conflict of interest

A few postgraduate researchers experienced a pressure/tension in ensuring that their PhD research findings would have an outlet for publications and hence there were a few lived experiences captured around this context. Sean's crafted story 'transparency about publishing research' described his experience of confronting an issue about publishing research due to a conflict of research interests of his and his industry collaborator.

Sean experienced the difference in the perspectives of the postgraduate researcher and the industry collaborator of the outcome of the research collaboration. Sean was interested in writing research papers based on his research whereas the industry collaborators were keen to get the research work completed first as an output of the research funding allocated to the postgraduate researcher. The strategy for research publications was not discussed transparently by the industrial collaborator in the beginning of the research. Sean felt disappointed when he understood about it nearly at the completion of his work in collaboration. This conflict of interest created a tension between him and the research collaborator.

On the other hand, Susan's experience of working with an industry collaborator in her PhD was motivating and she mentioned that the industrial collaboration did not affect the process of publishing research papers. Susan described that the company was a small spin-off setup initiated by the efforts of her supervisor in an industrial partnership. She made it clear to me that her research samples were different than those which the company was interested in testing. In that period, the company borrowed a particular instrument for a short period of time and she had the advantage of working on that new instrument. Furthermore, due to the limited availability of the instrument, she could develop the skills such of time keeping, organisation and planning. She was also encouraged to publish research papers so that it reflected well on the company's involvement in the research activities.

Both Sean's and Susan's experiences were opposite when I compared them in the context of publishing research material. Although my aim was to study the positive or negative impacts of industrial collaboration on nanoscience research publications, reviewing above and similar experiences in other crafted stories, I now viewed something differently than I had previously, widening my worldview about researchers' life worlds where they tackle issues associated with the industry collaborations during the research writing process.

Judging the research through different lenses

When it comes to the research publications, many postgraduate researchers commented that being first author in a publication was of particular importance to them. The researchers considered that the rank in the authorship of the research paper reflected the amount of work contributed to the research paper. There were a few examples detected describing this perceptions of researchers. Being a postgraduate researcher, my thoughts also resonated with what they said in their interviews but I was interested in understanding why it is an issue in nanoscience research.

Ciaran's crafted story 'judging work from lenses of other disciplines' described tensions about the authorship issues when the researchers from different disciplines reviewed the same research work. Ciaran reflected on his experience of negotiating the authorship rank in a research paper and commented that authorship ranking in his paper was biased initially. He perceived that the research work when judged from the lenses of other disciplines was responsible for such a bias. He believed that the judgement disregarded the enormous amount of time Ciaran had invested in the collaborative work. He commented that it was important to clarify the role of each researcher and their contribution in the research paper from the beginning. Although Ciaran remarked that it was not intentional and could have happened due to the lack of awareness of the researchers from other disciplines about the details of that particular task in other disciplines. Ciaran's supervisor played a role of 'arbiter' to resolve the tension. He added that many of his colleagues experienced similar authorship conflicts and they experienced emotional strain when they were not given credit of their work.

Sense of responsibility

Michael described his feeling of ‘a sense of responsibility’ in writing the research papers in nanoscience as the area is comparatively new and unexplored. Further he believed that the researchers are pioneering the work of generating literature in this new research area. He perceived that the newness of this research area made the researchers feel fortunate as they had many things to explore however it accompanied the “baggage” of a sense of responsibility. Similarly, Gordon stated that the research in material science at a micro-scale has reached a saturation point while there is a whole lot of new, unexplored world at nanoscale. He claimed that researchers within his generation are given the responsibility to uncover the nanoscience world and contribute to it.

There were other descriptions of experiences which broadened my horizon of understanding in this context. Eva believed that majority of the research publications in this area promoted applied research work and the journals assumed a certain level of understanding of nanoscale techniques and instruments (such as XRD, SEM, TEM and AFM). She articulated a particular problem when she was trying to interpret a graph from IR microscopy and XRD which she had no experience in. She experienced the inadequacy of good review articles in this area which explained the scope of the specialized nanoscale instrumentation in research. She had to read some basic disciplinary journals, books and also take help from research colleagues to obtain such information. Although, she believed that such an exercise was expected for any new interdisciplinary research area.

Eva described her research to be ‘interdisciplinary’ therefore I probed further to understand how she approached such an ‘interdisciplinary style’ of writing. She discussed that she did not adapt to any particular style or approach when writing neither did she prepare the manuscript having a particular research journal in mind. Selection of the journal for communicating the research work was a call of her supervisor. Aoife's experiences were similar in this context. Similarly, Adam mentioned that writing for journal publications was a different experience but it was not specific for the nanoscience research. Eva, Adam and Aoife's experiences portrayed that researchers experienced difficulties in searching basic level of information from nanoscience journals. Although, one can argue that scientific research papers are always specific and specialised for specific disciplines or special interest groups; it was evident that novice researchers experienced challenges in extracting or locating more basic information related to their research through research journals in that area. As a result, they had to retain strong links to fundamental books and papers of the disciplinary domain. There were no particular concerns about the style of writing in nanoscience research publications. Other than that, there was a common tendency observed in most of the researchers regarding selection of journal for publishing their research work. In a majority of cases, the selection of journal was the call of the supervisor. Although, postgraduate researchers often stood as leaders in the construction of the manuscript for the journal papers, they trusted their mentors/supervisors experience in this area and followed their call.

In summary, there was a broad range of lived experiences detected, examined and analysed under the context of 'publishing research in nanoscience area'. It was a source of mixed emotions ranging from frustration, vulnerability, concern, struggle, feeling neglected, challenged and responsible. The examination brought to light some new and unknown perspectives about publishing research in this area and ultimately contributed to the understanding of nanoscience research.

5.3.3 Changing roles/expectations

Working in the nanoscience area went beyond a cognitive task of research for many postgraduate researchers. For some researchers it became a platform for developing leadership and managerial skills. Many experienced their definitive role in the decision making process in their research involving more than one discipline while a few experienced the feeling of vulnerability under specific circumstances and needed to develop negotiation skills during the research. The researchers believed that nanoscience taught them the art of politically managing people including their supervisors and collaborators but they experienced tensions due to different expectations of research collaborators from other disciplines. I included 3 crafted stories in the appendix 2 (crafted stories) to discuss the themes and analysis in this context. The stories are the following.

- Dealing with the expectations (Adam)
- Constructing results and perspectives of disciplines (Anna)
- Politics of research (Amanda)

Dealing with the expectations

Adam's crafted story 'dealing with the expectations' described how postgraduate researchers from one group had a limited knowledge of the challenges of their other collaborative groups and their interest was limited only to the shared research material. For example, Adam noticed that the researchers in the biomedical group were not particularly aware of the complexity of the problems Adam faced in his experimentation. He recognized that the group meeting was not a place to share his problems or discuss the research related issues as he could not find any intellectual resonance with other members of his group. He favoured independent (separate) meetings with his supervisor from an engineering discipline for discussions although he was placed in the biomedical group in his research and needed to attend their meetings.

Adam experienced an intellectual ‘deserting’ or a feeling of ‘being detached’ in the group. His research interest was in examining the plasma parameters/properties for the development of specific chemistry layers of fixed thicknesses, although he discussed that such layers had applications in the biomedical area in which the rest of the group members were interested. He understood a gap between the expectations of other researchers’ from his research and what he could offer to them practically from his experimentation. He perceived this gap as a result of misrecognizing/underestimating the disciplinary challenges by the researchers from other disciplines. He considered that his research performance was mapped (or judged) by other research disciplines in the meetings and they became uninteresting for him due to the lack of opportunities to discuss his problems.

Interestingly, Ruth and Adam, both of my research participants were from a same larger research cluster. When I went back and forth between Ruth’s crafted story ‘Multiple disciplines at the instruments’ and Adam’s story ‘Dealing with the expectations’, I understood that both had different experiences of working in the same research cluster in similar situations. Reviewing these stories in hermeneutic analysis circles, it appeared that Adam considered the research cluster as an ‘intellectual desert’ and exhibited little interest in attending research cluster meetings, whereas, Ruth received expert help from other disciplinary experts for her research. When the two stories were compared, they were suggesting that not all individual research projects in the nanoscience research cluster are rooted in multiple disciplines necessarily.

Politics of managing people in nanoscience

Adam in his story 'dealing with the expectations' described his engagement with the politics of managing both the supervisors and achieving his research objectives. Adam was meeting his second supervisor only for the administrative updates of his project while his meetings with his first supervisor (from his discipline) were mainly to discuss research findings and seek suggestions. He favoured the meetings with his first supervisor as they were targeted to discuss the inputs, suggestions and experimental challenges. He referred to the biomedical group meetings as 'planning meetings'. He perceived these planning meetings as a place to discuss the timelines and they were not of great interest to him research wise. Another researcher Eddy had similar experience in relation to research group meetings. He described these meetings as 'formal' with the purpose of conveying updates of the research to the secondary supervisor and other group members as they did not give any constructive suggestions or inputs in his research. On the other hand, he experienced that the meetings with the first supervisor included lots of 'bouncing of ideas' and these were mostly informal.

Anna's experience of meeting her supervisors was different. In her story 'constructing results and perspectives of disciplines', Anna mentioned that meeting both her supervisors separately was only for their convenience as they had different schedules. She discussed that she invested double the time for the meetings but each supervisor brought knowledge from their own discipline and their expertise was important in making decisions in the research. She commented that the perspective of the other discipline shaped the structure of the results in a concise and presentable manner. From the previous story 'Not all instruments are central', I interpreted that Anna perceived distinct boundaries of disciplines when she worked with nanoscale instruments. By reading both stories holistically, I understood that Anna was not expecting to master the approach (or technique) grounded in another discipline however she respected the perspectives of other disciplines and tried to adapt it locally in her research.

Amanda's crafted story 'politics of the research' described her experiences of working on her PhD topic and carrying out some industrial collaborative research work initiated from her supervisor's political interest in the research funding. She struggled to balance both pieces of work simultaneously in her research which at times annoyed her. But at the same time, she pursued the industrial collaboration as a platform to develop her professional connections. The story dominated her reflection and opinions, but it testified the strength as a phenomenological data as these reflections and opinions were grounded deep in her experiences that she articulated elsewhere. Amanda's story portrayed her perceptions of her duty, interest, involvement and expectation and described her involvement in the politics of nanoscience research.

Taking decisions

The postgraduate researchers articulated their experiences of taking initiative, taking charge of their project, making decisions and bringing a new knowledge output as a result of one or all. For example, Mark described his experience of participating in a technology transfer workshop He perceived that the nanoscience research community is curious about new collaborations and considered it his responsibility to communicate the research finding as an expert in this new and applied area in order to attract other researchers, employers and industry collaborators. At the conference, he was approached by a researcher working on Solar cells, who exhibited interest in Mark's work and wanted to explore the possibility of using nanowires for solar cell applications. Mark took that opportunity, organised meetings and followed the work until a new research collaboration was established successfully. Such an initiative allowed him to recognise the commercial value of his research which was not in the original research plan.

Reviewing all the crafted stories in hermeneutic circles I interpreted that engaging in the politics of research made researchers understand their 'being' and develop skills to achieve success in their research. In a few cases, the larger research clusters complemented researchers to understand the broader goals of the research project to which they were individually connected. It also made them aware of the contribution that is expected of to fulfil the group research objective. Working in broad research clusters was challenging for other postgraduate researchers as they struggled in order to sustain with the expectations of other disciplines. The politics of managing people was not limited to the supervisor and colleagues in the research cluster but it extended up to the larger research network including the collaborators and reviewers of research journals. By getting involved in such politics, the researchers could identify new opportunities to expand their research and thereby altering their identity with new dimensions. The research groups, conferences and interactive meetings were not just a platform for exchanging knowledge but they were also shaping the researchers' identities/roles.

5.3.4 Conferences, workshops - simplified venture for knowledge world exploration

Conferences and workshops provided postgraduate researchers with opportunities to establish their identity in the research community. Many researchers stated that the conferences and workshops were great in terms of interacting with researchers working in similar areas, sharing the research findings and keeping up to date with recent research activities in the area. My own views were equally committed with what nanoscience researchers said. However, I was further interested to explore if the researchers describe any new or different experiences which were specific to nanoscience.

Many postgraduate researchers described nanoscience conferences as a project to get exposure of the ideas outside their discipline in a simplified manner. They appreciated the conferences, not because they can listen to the new and informative presentations from other disciplines, but they believed that these presentations explain complicated research recipes in a much simpler way that everybody can understand. Most postgraduate researchers perceived the nanoscience area as broad and including many disciplines. Therefore, they anticipated that the listeners at the conference would be from a wide range of disciplines. Eva discussed, when she presented her poster at a conference that she viewed the researchers from other disciplines as a 'non-specialist' audience and tried to communicate her research findings in a simplified form. She discussed that such a perspective made the discussions with researchers from other disciplines more constructive. Olan in his story 'communicating 'what' matters' described his experiences of communicating the research findings at a conference. He perceived that nanoscience conferences brought together the researchers with a diverse interest therefore communicating 'how the research can be useful to others' was important.

Brian mentioned that a few material conferences he attended in past were very broad and 'overburdening' for him. He attended many presentations which were about materials, precisely nano-materials, but not of interest to him. His research was focused on the theoretical aspects of a certain material and he had no interest in the other research areas in nanoscience. He felt being 'overburdened' to listen to all the talks under the 'nanotechnology' tag as he believed that it was of no benefit to his knowledge. Brian preferred attending specific conferences on his particular research interest where he met with people doing similar research. Another similar experience was described by Ross where he felt that he was asked to attend a 'commercialisation' meeting by his research head and supervisors when he had no interest in participating in that conference. He commented:

> *"I was there for a day in MMM commercialization conference but it was total waste!! It was nothing to do with research. It was more for commercialization and I think they were trying to drag the students."*

There were multiple accounts of researchers' interests, perceptions and opinions of conferences and workshops in the nanoscience area. The majority of the researchers agreed their decision to participate in the research conferences and workshops was proactive in terms of knowledge gained. Although they perceived a certain level of a disciplinary/cognitive barrier at the nanoscience conferences due to its broader and inclusive nature, they made efforts to overcome these barriers by a common vocabulary or simple explanations. Although some researchers believed conferences as hubs to explore the knowledge world of other researchers, others claimed to have restrained their participation feeling that nanoscience conferences were overburdening for them, or they did not add anything new to their knowledge world. Further, there were mixed accounts in relation to professional workshops such as technology transfer and commercialization. From the point of view of a few postgraduate researchers, participating in a commercialization workshop was not seen as productive activity while others discussed professional workshops such as technology transfer as a platform to meet other researchers for sharing ideas and pioneering new research links.

5.3.5 Postgraduate researchers being the centre of cognitive disciplinarity

The researchers experienced many situations in their research which triggered their sense of responsibility, decision making skills, pressure and authority. The examination of experiences in the hermeneutic circles depicted the different roles researchers played during their research. I included 3 crafted stories in the appendix 2 (crafted stories) to discuss the analysis in this context. The stories are the following.

- Bringing equal responsibility (Mick)
- Working together (Damian)
- Hierarchy of role: knowledge producer and communicator (Jenny)

Playing an important role in the decision making process

A few researchers experienced another sense of responsibility as they considered themselves as a 'solo spokesperson' of their knowledge. They argued that, although, the new knowledge developed originated on the background of multiple disciplines and was guided by the experts (supervisors) from multiple disciplines; none of the experts (supervisors) individually had the same kinds of in-depth knowledge of the entire project that they (postgraduate researchers) had. Therefore, the postgraduate researchers perceived that they had to act smart and politically balance what to say/write in presenting/writing the research as they were introduced to the concerns/specifications from multiple disciplines. The idea that such a new knowledge was examined against the standard and criteria of each associated disciplines resulted in tensions in postgraduate researchers' life worlds. Maria, a biology researcher, described her experience of presenting the research finding at chemistry symposium. She commented that she had to learn and add details of statistical methods and uncertainties in her presentation as she perceived that the audience could be curious about statistical details of uncertainties.

The researchers also expressed that liability of knowledge of one of the involved disciplines was completely on their shoulder. They discussed that the supervisors more often handed over the responsibility of training the new postgraduate researchers or undergraduate trainee to them. Although one can argue that it is a common culture in any research laboratory, the nanoscience research laboratories were also merged in the similar culture. The researchers also perceived that when the research involved knowledge of more than one discipline, they secured a central/important role in the knowledge exchange in the research laboratory. The postgraduate researchers played different roles: as a trainer for the undergraduate students and novice researchers in the group, and as a co-ordinator of knowledge developed in the research. Also, the research laboratories where nanoscience research took place turned into hubs where postgraduate researchers were trained for their professional development as a teacher and/or as a research professional.

In Mick's crafted story 'Bringing equal responsibility' he described his experience of explaining the biochemistry perspective of the research to his supervisor from a physics discipline. He considered his input to be important in interpreting the result against the knowledge of both disciplines. His supervisor looked at the results of mathematical models only analytically while Mick brought a biochemistry perspective in the interpretation. Mick tried to understand the mathematical model and equations first, and then linked his biochemistry knowledge to explain the equations. As a result, he could modify the research findings to make more sense. The research work was a cumulative effort from both Mick and his supervisor but Mick played a central role in constructing new and meaningful knowledge at the junction of both disciplines. He spanned the disciplinary boundaries to gain a new understanding of mathematical equations with a biology perspective although he described that the entire process was challenging. He did not expect his supervisor from physics to be familiar with all the concepts of cell-biology and biochemistry and believed that it was his responsibility. He requested his supervisor for more explanation to understand the mathematical equations, but at the same time, he had to express his authority of his knowledge of biochemistry confidently to construct the new and meaningful knowledge.

In the story 'working together', Damian described a similar experience of working with his supervisor from a biology discipline in the optics research laboratory. He mentioned that he did not expect many inputs from his supervisor in biology when he was facing problems while developing an optical setup for his experimentation. He believed that his supervisor authorised him for taking decisions when the issues were related to physics aspects of the research. In his stories, he emphasized on the 'trust building' when researchers from multiple disciplines were working together.

Hierarchy in role as knowledge producer and communicator

The postgraduate researchers played a central role in i) organizing/planning research in the laboratory, ii) taking cognitive decisions related to the research, iii) conducting experimentation and iv) discussing the results at different settings (group meetings, conferences). However, there were mixed views about their role in the decision making process when it comes to collaborative work in association with the industries. Jenny's crafted story 'knowledge producer and communicator hierarchy' described her experience of working with an industrial collaborator. Jenny described that although she did not communicate with the collaborators directly during the research, she played a central role in the process of knowledge production. She perceived a misbalance of hierarchy in her role as a knowledge producer and as a communicator/organiser in the industrial collaborator. Ashlyn and Liam's experiences were similar to Jenny's in this context. Liam's reflection of his research in the collaboration with the industry is given below.

> *'The connection with the company is mainly through the supervisor so companies don't know who are involved in the actual testing process. We do not get in direct contact with the companies as we are just the PhD students!….I always get only second hand emails which DDD would pass it on to me. Sometimes, DDD would email me separately and not even forward me the whole thread. It will be lot more valuable if I could get to contact them and work with them first hand. It is important for me to establish the contact, have my name in it at some stage! And, not just that, even to know what the company is really interested in from us! The company should tell the researchers what the issue is!'*

From above and other similar stories it was clear that the postgraduate researchers had a main/important position in the knowledge production in their research, no matter if the collaboration was between different research groups, or between industry and the university. At the same time, it was seen that their authority in the research collaboration process was flexible/changing following their role as a communicator/organiser of the collaboration. In all circumstances, researchers were in charge of the knowledge output associated with the research. Such responsibility was imposed on researchers to a greater extent when they were solely representing new knowledge produced on the boundary of multiple disciplines. The researchers also expected a clarity or transparency during knowledge exchange.

5.3.6 Defining ‘nanoscience’

When the researchers were requested to define their research area the majority of them labelled it as ‘nanoscience’. They gave reasons such as, their research involved use of different nanoscale instruments such as AFM, TEM, SEM, or they were working on the nanoparticles, nanocoatings and/or nanofilms. Although there was an influence of the core disciplines on their thinking as the majority of the researchers preferred to be seen firstly as ‘disciplinary graduates’. They also called themselves ‘nanoscience researchers’ saying that their research was related to nanoscale and it involved the nanoscale instruments or nanostructures/ nanomaterial. There were many nods on the ‘broad’ nature of the nanoscience research area. They commented to know ‘very little’ of all science and engineering disciplines if they considered that all disciplines were merged together under the title ‘nanoscience’. They perceived that the knowledge output of their research was of interest to a few researchers, the cross-section of such researchers although was not restricted to their core disciplines. They favoured to remain associated with their core disciplines but simultaneously not being very dogmatic about it. They considered their research in the nanoscience area was more research problem centric and required both disciplinary as well as boundary spanning knowledge and skills.

5.4 Summary

This chapter revealed researchers’ emotions, tensions, concerns, challenges, issues, vulnerability, strengths, integrity, feeling of intellectual isolation, dissatisfaction and the efforts of planning and management in different life world situations. The challenges experienced by the researchers will eventually contribute to the larger debate of how the knowledge is produced in nanoscience area, to my end/interest, the examination of experiences illustrated how the researchers' perceive and understand their research.

My continuous dialogue with the researchers' experiences (depicted in the crafted stories) in hermeneutic analysis circles resulted in the primary, secondary and holistic themes. These derived themes and interpretive writing together gave a 'felt sense' of how researchers experienced the phenomenon of 'researching in the nanoscience area'. In the next chapter, I discuss the essential meaning of the phenomenon derived from a further interpretation of the data.

As explained earlier, one aspect of the hermeneutic interpretive analysis is going back to the main/research questions with a greater understanding of the phenomenon studied in the light of the participants' lived experiences [Giles 2008]. With the greater understanding of the phenomenon, I hope to address my research questions. It is discussed in chapter seven.

Chapter 6 Understanding the phenomenon of ‘researching in the nanoscience area’

6.1 Introduction

The previous chapter discussed the holistic themes constructed by dialoguing with the research data in the hermeneutic interpretive cycles. In the analysis, I visited the researchers’ descriptions of ‘researching in the nanoscience area’ by reading the crafted stories several times and I validated the researchers’ experiences and reflections. Van Manen described the process of validation of the experiences as the ‘validating circle of enquiry’ in which the researcher learns to insert him/herself in the tradition of scholarship and recognizes the experiences which the researcher on his own had or could have had [van Manen 1997]. For me, the validation process was my thoughtful insertion in the ‘hermeneutic phenomenological’ tradition explained throughout my involvement in the research data as an education researcher, as well as, as a postgraduate researcher. In this enquiry I carried my baggage of experiences of ‘being a postgraduate researcher’ however the context ‘nanoscience’ was new to me. Therefore, I validated the experiences if those were about the postgraduate researches’ ‘being’, and I was confident about their phenomenological nature and their relevance within the context of the research. There was ‘phenomenological nodding’ involved when I recognized the significance of the experiences in explaining the meanings of the phenomena of interest.

In this chapter, I present the central or essential themes that emerged from the hermeneutic interpretive analysis of the postgraduate researchers' experiences and elaborate on them further. This process of developing the essential themes is referred to as 'explication' as described in chapter four. These essential themes are the heart of the phenomenon of 'researching in the nanoscience area' without which the phenomenon cannot be explained fully and they give a newer understanding of the phenomenon.

Once such understanding is achieved, the spotlight is then placed on checking what these essential meanings contribute to the understanding of the disciplinarity and attributes, knowledge, skill and competence associated with nanoscience. It is described in the following chapter. Chapter 7 also includes a discussion on the quantitative survey and the concluding remarks.

6.2 Essential themes

Exploring the essential themes from the hermeneutic phenomenological examination of the postgraduate researchers' experiences is central to the reconstructed meaning of the phenomenon of nanoscience research. These themes were derived by going through the hermeneutic circle of analysis iteratively until reaching that explanation/meaning which makes it inseparable from the phenomenon, in other words the meaning was essential in order to explain the phenomena [van Manen 1997]. From the holistic themes that emerged from the interpretive analysis and setting a continuous dialogue with the crafted stories by interpretive writing, I derived three central or essential themes describing the essence of the phenomenon. These essential themes are discussed in this section.

6.2.1 Boundary spanning

I have called the first essential theme 'Boundary spanning'. It is often cited as a business skill in relation to the organisational management required to build connections, inter-relationship or partnerships between the companies and/or personnel [Kaplan 2012, Battard 2010]. It refers to the efforts of the industries/companies to bridge the gap between the employees working at different levels, or between the company and its distributors for accomplishing a particular objective. I have selected the term 'boundary spanning' to explain the postgraduate researchers' efforts at the disciplinary boundaries to understand nanoscience research. There were two streams of boundary spanning observed. The first stream involved the postgraduate researchers who experienced the boundary spanning as a 'resistive movement' due to their strong disciplinary attitudes and they preferred 'borrowing' the results from the other disciplines in order to complete their research objectives. The postgraduate researchers therefore were connected to the knowledge of other disciplines superficially. The second stream involved the postgraduate researchers who took additional efforts in order to minimise the cognitive struggle at the disciplinary boundaries in order to understand their research. They spanned the disciplinary boundaries with the help of word-nets, exploratory words, images, simplified explanations and discussions and understood nanoscience research. The examination of researchers' experiences revealed that researching at the disciplinary boundaries in nanoscience was perceived and experienced as a challenge by the researchers but they adapted different spanning pathways/methods to deal with it.

6.2.1.1 Minimising the disciplinary barrier with word-nets, images and exploratory words

When I reviewed the researchers' descriptions of their experiences, there were stories articulating experiences of boundary challenges. For instance, Alan described his confusion with the phonetics of words such as 'lysing' and 'aliasing' which had different meanings in biology and physics/electronics. Another story of Thomas explained his problem with the use of the word 'control' when he was talking with toxicology researchers in a collaborative project. The word control was referred to by the toxicologists as a 'reference' or 'base experiment' performed to compare the effect of dose and hence it was referred to as a data. Thomas, with an engineering background, perceived 'control' as a regulation/adjustment of some tool or equipment and looked at the values as optimization parameters. Mark faced similar challenge while reading biochemistry and pharmacology journals to relate word pairs such as agonist and antagonist, and ligands and inhibitors. In short, the words, terms and phrases did not have the same meaning in each other's knowledge world!

Although the disciplinary boundaries led to the complexities in understanding the meaning of words, the boundaries were spanned by the researchers locally by making use of word-nets, exploratory words, diagrams and images as far as possible. It was observed that the researchers started building their own adapted vocabulary with a minimal hierarchy necessary for that particular research application in such a way that everybody associated with that work/application could make sense of it. These were broad exploratory words often explained with images or diagrams. Furthermore, the researchers also made use of 'word-nets' when they explained their research to others.

The development of the 'word-nets' involved gathering the words of similar meaning associated with the query, for instance, the words classification or categorisation are related to grouping. Such words were archived by listening to the conversations, interacting with other researchers during the work, and reading books, research papers and online resources. Alan understood the meaning of word 'lysing' as 'rupturing' or 'breaking of cells' through images; Mark discovered the relational meaning between pairs 'agonist, antagonist' and 'ligands, inhibitors' by reading the research papers and identifying their common/shared meanings. In short, such word-nets, exploratory words, figures and diagrams meant the disciplinary perspectives were comparable with each other. Furthermore, they triggered the rebuilding of the 'knowledge base' with the addition of new vocabulary; and by understanding the new meaning of techniques/protocols from other disciplines. The researchers adopted it when they were explaining their research to someone from a different discipline during their group meetings, conferences or laboratory visits. They articulated that 'word-nets' made the conversations more meaningful and they could express themselves in a better way in front of an audience with a broad disciplinary mix. For instance, Maria, a toxicology researcher interacted with the researchers at a chemistry symposium in her institute. She described that she could minimise the gap between their research interests by sticking to a basic simplified explanation of her research work and exploratory words. On another occasion, Paddy started using words 'blood plasma' and 'ionic plasma' to avoid confusion between the word 'plasma' when talking about his research of plasma treatment for food safety.

Even as an interviewer, I experienced the researchers' adaptation to the word-nets, diagrams and images when they discussed their research. Those who were familiar with my physics background continued the use of physics terminologies without any hesitation while others tried to explain their research problem at a much more basic level using the exploratory words. The researchers appeared to be supporting the use of exploratory words, word-nets and images to minimise the barrier of communication through disciplines and span the disciplinary boundaries.

6.2.1.2 Superficial boundary spanning

A few postgraduate researchers experienced the boundary spanning as a resistive movement. They preferred/welcomed opportunities to borrow the existing knowledge of other disciplines to use as 'tags'. Although boundary spanning was evident in such borrowing the researchers judged such borrowing on the moral background of 'trust'. The researchers trusted the knowledge, methods, techniques and protocols from other disciplines and they borrowed the knowledge from other discipline by fully trusting their colleagues' expertise in that particular discipline. For instance, in Anna's story 'Not all instruments are central' described in the section 5.3.1, she expressed a resistance to learn the technical knowledge related to particular instruments (SEM and AFM) as she considered to be 'non-central to her learning'. Therefore she simply adopted the results provided by her colleagues and included them when compiling her research outcomes. In another context, Alan discussed his confusion about a particular biological assay and how his colleague from chemistry was of great support to him to take the decision to proceed further in his research. Such borrowing in both the above cases was based on trust building. In these cases, the knowledge may have migrated across the disciplines but the knowledge bases and understanding of postgraduate researchers working on the project were not significantly changed, as they resisted adapting new meaning so easily, indicating a superficial boundary spanning. Similarly, the interpretation of Ronan's story 'AFM' explicated that Ronan did not consider that the TEM data collection was a 'learning experience' as it was carried out by a technician in the laboratory. Furthermore, he raised a question in relation to the comments made by his colleague (from biology) regarding the use of AFM tool. I considered this to constitute his reflection on his learning of AFM handling skills which he perceived were specialised disciplinary skills. He therefore did not agree with his colleague's belief that she had used AFM machine in her research.

In the superficial boundary spanning, the notion of the 'language' or 'vocabulary' of the involved disciplines was not a main concern, instead the focus was at the instruments or the techniques at the nexus of disciplines. It was observed in many of the above cases that the researchers did not tend to give much importance to the 'learning' of the techniques or instruments from other disciplines. The motivation behind using the particular equipment or technique/s was purely in relation to their advanced technological paradigms or applications. Such boundary spanning indicated the multidisciplinary character of nanoscience where the constituting disciplines although integrated to construct a new knowledge remained connected only superficially. Furthermore, the knowledge, protocols and methods of other disciplines were not questioned during the integration and were simply accepted by the other disciplines smoothly to produce a new project specific knowledge.

6.2.1.3 Boundary spanning and intellectual friction

There was one story 'sharing and questioning information' which described Ciaran's experiences of interpreting XPS data. Ciaran perceived that the boundary spanning involved a greater friction (or struggle) at times when he approached the research problem with a thoughtful mind, and raised queries without just accepting the outcomes achieved from the techniques from other disciplines. Ciaran had to explore the analysis from the chemist's perspective in order to track down the root cause of the misinterpretation of XPS data. He approached the problem with a thoughtful, enquiring mind and applied his own disciplinary knowledge to ultimately resolve the confusion. Ciaran's story exhibits his struggle while boundary spanning. His reflection that 'one should question the techniques applied in the research to bring strength to their knowledge of their own research' is therefore referred to as a skill for spanning the disciplinary boundaries.

Mick's story 'Sharing equal responsibility' added another dimension to boundary spanning in the requirement of having the skill associated with carrying the responsibility of the knowledge holder. Similar to Ciaran, Mick also believed in an enquiring approach where new knowledge can be developed by combining the methods and/or knowledge of two or more disciplines. He felt a sense of responsibility to accurately communicate his disciplinary knowledge (of biochemistry), answer all the queries from his supervisor (physics), as well as demand more explanations from others to understand their perspectives when necessary. Damian and Mick's reflections in this context suggested that such boundary spanning resulted in situating the disciplinary knowledge in an awkward position, as both researchers and the supervisors from different disciplines had to answer sometimes very trivial discipline-specific questions. These experiences highlighted a healthy intellectual friction amongst postgraduate researchers while spanning the disciplinary boundaries. Reading the stories described by Ciaran, Mick and Damian holistically, I interpreted that such intellectual friction was present in many research projects in the nanoscience area which brought together physicists, chemists, biologists and engineers. The friction can be minimized by acknowledging the importance and contribution of the knowledge of each discipline while at the same time keeping an enquiring approach.

Experts in cross disciplinary communication research stated that a diverse team can contribute innovatively and effectively when the team members have a social comfort at the workplace and do not fear asking the simplest possible questions [Abicht, Freikamp and Schumann 2006; Van Horn, Fichtner and Cleary 2009]. In connection with the researchers' 'being', it was seen that many postgraduate researchers experienced a similar social comfort that allowed them to share their problems, queries and expert knowledge and hence develop the new knowledge formed at the junction of two or more disciplines by minimising the struggle.

6.2.2 Mapping the disciplines- interests, performance and perspectives

The second central or essential theme is 'mapping the disciplines'. Researchers working in the nanoscience area deal with other researchers, principal investigators, scientists, industry personnel, reviewers, editors of scientific journals, examiners and collaborators. Their involvement in the research brings an experience of 'mapping' where the researchers perceive that their research is judged by others. Furthermore, the postgraduate researchers themselves tend to map (judge) the disciplines, interests and perspectives of other disciplines. Although, all postgraduate researchers often have their work judged by a wide range of people, nanoscience research brings together the researchers, industry personnel, reviewers, examiners and collaborators from different disciplines and therefore the mapping is done by different disciplines. Thus, mapping is described as a product of bringing many disciplines together to evaluate and judge the research and researchers.

Experiencing mapping i.e 'judging or being judged' by different disciplines involved in the research emerged as a central or essential theme of researchers' lived experiences, although the subject space of mapping was diverse. A few postgraduate researchers experienced mapping in the form of criticism of their work by others who 'mapped' the researchers' performance from the lenses of other disciplines. While some felt that mapping stimulated their role change as a leader, as knowledge generator, as a decision maker, as a negotiator or as a communicator others had to change their research strategy as a result of the mapping. The researchers portrayed the practices they followed as a response to the mapping through many lived examples which in turn informed the skills and competences necessary to successfully work in this area. Managerial skills and competences such as decision making, initiating new research tasks, organizing planning meetings, sharing responsibility of knowledge transfer in the research group, effectively communicating the disciplinary strengths to researchers of other discipline and time keeping were practised by the postgraduate researchers.

6.2.2.1 Mapping the performance: communicating challenges and limitations

Adam's story 'Dealing with expectations' described how his work on developing a nanoscale polymer coating for a particular bio-medical application was judged/mapped by other researchers in his group. He felt that the demand for developing multiple types/number of coating imposed by other group members was impractical as Adam's research was concentrated on studying the process, parameters and optimisation techniques for the polymer coating. Such knowledge was important and crucial for his disciplinary understanding but he experienced disconnectedness or intellectual solitude due to the gap of understanding of disciplinary perspectives within the group. A similar experience was shared by Eddy who described that there was often a 'bouncing of ideas' discussion when he interacted with his supervisor from his discipline. While the other group members in the broad research group meetings did not contribute anything in these discussions. Both Adam and Eddy preferred their individual meetings with supervisors of their discipline to discuss the challenges in their work. Following these examples repetitively in the hermeneutic circles, I interpreted that such mapping activity resulted in situating the researchers in a position where they may lose interest in the larger goal of the research project. Effective communication of the research outcomes as well as the challenges and limitations from each of the involved disciplines in achieving the research objective can become important in this situation. It can cultivate an understanding of the challenges and limitations of the disciplines amongst postgraduate researchers involved in that research and thereby minimize the difficulties due to the mapping of disciplinary perspectives.

Ciaran's story 'judging research from lenses of another discipline' indicated that the researchers tend to map others' performance while carrying a strong disciplinary attitude, occasionally resulting in conflicts about the authorship in the research paper. Ciaran experienced that such mapping disregarded the enormous amount of time he had invested in contributing specific knowledge of his discipline in the collaborative paper. When I read all the above stories as 'parts' and as 'a whole', my horizon of understanding about how the researchers experienced the 'mapping' expanded. The skill of i) explaining strengths and limitations of the disciplines and ii) maintaining transparency about research contribution in the communication across the boundaries of disciplines can be important in the context of mapping.

6.2.2.2 Mapping interests: taking a step back

A few researchers mapped the research activities such as commercialisation and technology transfer workshops, industry collaborations and conferences based on the scale of personal motives and/or research interests. They perceived a contradiction in their motives and/or research interests with the themes/objectives of such events. For instance, Ross considered his participation in the commercialisation workshop as a waste of time. He exhibited the least interest in that workshop as he considered it to be a complete mismatch with his research interests. Similarly, Brian commented on an international nanotechnology convention conference as an overburdening experience. He claimed that it did not add anything new to his existing knowledge of her research project. Colm argued that his participation in a particular conference was purely influenced by his research collaborators and it did not have a great connection with his postgraduate research. In Amanda's story 'politics of research' she argued that there was nothing common between her research work and the work she was conducting for industry collaborator in the laboratory. The collaboration was perceived as a potential funding resource by the principal investigator and the industry/company used laboratory resources purely for a sample testing process. Amanda referred to her contribution in the industrial collaboration work as 'inevitable' due to political reasons (research funding) and considered herself 'dis-connected' from her research and working without any creative research inputs. From the examples described by the researchers, it was clear that the mapping of the disciplines, interests and perspectives carried out by the postgraduate researchers was leading them towards the feeling of being 'dis-connected' or 'isolated' from the broader research goals of the broader nanoscience community.

While on the other side, some researchers symbolised the conferences as ‘activity sites’ or ‘hubs’ for bouncing ideas, networking and pioneering new research links and knowledge. Mark articulated his experience of stimulating a new research collaboration at a technology transfer workshop by keeping a track of conversations at the presentation. Olan believed that at such broad conferences, it was worth investing time to explain i) the motivation behind the research and ii) what the research output can offer to others. Maria and Eva promoted the idea of communication to ‘non-specific’ audiences at such events which involved the use of simplified exploratory terms. Many postgraduate researchers supported such a method of communication to ‘non-specific’ audience at the conferences. They described that such events encouraged them to become tolerant and put extra efforts into explaining their research to a wider audience. In educational paradigms, I could relate to the skill of communicating to a ‘non-specific’ audience to a broader forum of scholarship of transforming ‘knowledge as power’ from the hands of the presenter to the hands of audience, which in this case would be colleagues, researchers or collaborators in nanoscience research.

6.2.2.3 Mapping the perspectives and role: professional intimacy, involvement and transparency

There were a few lived experiences under the realm of mapping the perspectives and role. In these, the postgraduate researchers described that their involvement in the research was mapped differently from the people (principal investigator/supervisor and industry personnel) associated with their research. Jenny in her story ‘Hierarchy of role: knowledge producer and communicator’ described although she was a key person in the ‘knowledge production’ in her research in collaboration with the industry, her role as a ‘knowledge communicator’ was not transparent and/or authoritative. She was not always placed in front (or directly involved) during the communication. She reflected on her experience by commenting that a greater level of professional intimacy (understanding) and involvement between the industrial collaborator, principal investigator/supervisor and the postgraduate researcher would have resulted in better research outcomes. In another story 'transparency about publishing research', Sean discussed how the lack of transparency in relation to publishing research papers created tension during industrial collaborative research. Sean mapped the company's neutral attitude about publishing the research through scientific journals which on the contrary was perceived as vital for his own research. All the experiences described in this subsection were specific to nanoscience research in collaboration with industries. It may be the case that these lived experiences were not central to postgraduate researchers' 'being' in many situations. However, they did certainly add further meaning to the essential theme of 'mapping the disciplines- interests, performance and perspectives'.

Overall the crafted stories described experiences of mapping of disciplines, performance and perspectives and how it influenced researchers' 'being'. The mapping made them aware and responsible about their role in a positive sense while occasionally it resulted in a feeling of being 'isolated' or 'disconnected' from the group or 'reluctant' about networking and collaboration opportunities. If these researchers take a step back and reflect on their perceptions about the networking, collaborations, workshops and conferences, they could connect with the core purpose of these activities with a relaxed attitude and therefore enjoy their inclusion/existence in a broader research framework positively and constructively.

6.2.3 Understanding nanoscience in the laboratory: learning through informal teaching

The third essential or central theme is ‘learning through informal teaching’. It explains the postgraduate researchers’ efforts in understanding their research in nanoscience research laboratories. In PhD research, the ‘knowledge transfer’ in relation to the laboratory instruments occurs most of the times in an informal way i.e. the senior researchers train the novice postgraduate researchers to work on different tools/instruments in the laboratory, familiarise them with the research data and on some occasions, even provide them initial training for interpreting the research data. This tradition is followed by the trained researchers for the training of future researchers. In nanoscience research laboratories, most of the training of new researchers occurs in similar fashion. In recent literature, nanoscience laboratories have been identified as ‘technological hubs’ for knowledge transfer where the ‘teaching’ and ‘learning’ in relation to the instruments occurs in an informal way and the nanoscale instruments providing a common ground for the research work for many disciplines [Battard 2010].

In many stories describing the researchers’ learning of new instrumentation or techniques in the nanoscience laboratories, ‘learning by teaching’ was at a central position. When postgraduate researchers were new in the research laboratory, they greatly appreciated the role of senior postgraduate researchers as ‘informal teachers’ in facilitating the project specific knowledge. They continued this tradition of informal teaching for the new researchers and/or undergraduate trainees, coming from the same or different disciplinary backgrounds. Susan shared her experience of teaching the ‘nanowire growth mechanism’ concept to a chemistry undergraduate trainee. She explained that she had to read much more about the growth mechanism of nano-wires in order to teach that to the student and answer her queries from a chemistry perspective, although she only researched on one particular method during her PhD work. She described that the reading for teaching was helpful at the viva examination as her external examiner was a chemist. She reflected on her experience:

> *'If somebody wants to know about nano-growth mechanism fully then you cannot leave that particular part out in the conversation saying that you are not interested in top-down approach but just in bottom-up approach! It becomes imperative to understand something fully by ourselves first, if you have to teach it to someone. I suppose, the best way to learn something is to teach that to someone. For teaching, you need to understand it fully, you can't skip anything. Your desire to understand something new is automatically invoked when you have accepted that responsibility of teaching.'*

Susan's statement was a phenomenological reflection about her own experience of teaching which invoked her interest in reading about the 'bottom-up' approach, purely for the purpose of teaching. Her involvement in the informal teaching thereby became a way to understand the (nanoscience) research in a new perspective and paved a way for 'continuous learning by teaching'. Another experience of cumulative learning was described in Michael's story 'Sharing knowledge world'. Michael was teaching an engineering intern student about the effects of different (physical) parameters on nanoscale coating and their characterisation. Both of them were working on a new deposition system with separate coating materials. The informal teaching in the laboratory involved mainly interactive discussions with the intern regarding the system parameters. Michael mentioned that these interactions were fruitful to gain confidence about his own understanding and enhance his knowledge about the deposition system and its parameters. Michael discussed that he could understand the mechanics of the system in a greater depth and he could present the knowledge in front of his supervisors.

There were many similar stories describing the experiences of informal training at the instruments where the researchers interacted with colleagues from different disciplines. The researchers valued the informal teaching to attain project specific knowledge. Furthermore, the researchers perceived that their role as an ‘informal teacher’ for undergraduate trainees/new researchers influenced their own learning and understanding of their research in a broader way. In addition, the diversity of disciplines among the new research students or trainees changed their way of teaching, for instance some researchers aimed to simplify explanations of procedures or protocols. I also encountered a few examples where postgraduate researchers felt ‘isolated’ as they could not share and confirm their knowledge during the research with anyone. The researchers perceived that sharing knowledge and validating it through interactions with research colleagues brought a confidence in them to communicate the knowledge to a wider audience through journal papers, presentations or thesis.

In summary, the ‘informal teaching’ and ‘learning by informal teaching’ in the laboratories are blended well in the scholarship of nanoscience research. They are inseparable from researchers’ life world and emerged as essential themes. Informal teaching was viewed as a practical way to enhance the i) project specific knowledge, ii) knowledge transfer between researchers in laboratory and iii) communication skills by the researchers in the most obvious ways. The researchers looked forward to the opportunities of informal teaching and interactive discussions for their knowledge development.

6.3 Discussion: explicating the essential themes

The most recurrent word in the crafted stories was ‘nanoscale instruments’. A wide range of research projects were structured around researching with the nanoscale instruments in this area however their objectives were diverse. A few projects had distinct research objectives in their own disciplinary domains while others involved research objectives which complemented other projects in order to achieve a larger research goal proposed by the research cluster. The nanoscale instruments served an important role in all these research projects. They created a common platform where researchers from the same or different disciplinary backgrounds have met, interacted with each other, and exchanged research information. However, the interactions were not always easy as the researchers' experienced cognitive challenges when the multiple disciplines were converging at the instruments.

In many interactions about the nanoscale instruments described by the researchers, sharing the 'working knowledge' of the nanoscale instruments was identified as a prime intention. Such interactions were limited to learning the nanoscale instrument simply as a 'device'. However, interpreting the research data obtained from these nanoscale instruments and presenting the research findings was experienced as a challenging task by the researchers. From the examination of crafted stories, I interpreted that the researchers employed the knowledge of their own discipline and achieved boundary spanning. In other words, to gain the knowledge of nanoscience, postgraduate researchers required a knowledge base of their own discipline in the first place, and then, an insight of knowledge of other disciplines. The researchers began nanoscience research with their disciplinary knowledge and therefore they believed that such a disciplinary knowledge is their strength. For instance, Alan referred to it as the 'building blocks', Anna referred to it as 'essence' and Brian as 'expert knowledge'. The researchers first approached their research from the lenses of their own discipline and they enhanced their knowledge by interacting with research colleagues, reading journals and books. They explored the research world until they reached a point where they realized that they needed an insight into something else to better understand their research. Hence, ‘boundary spanning’ became essential as researchers explored a few different possibilities of crossing the boundaries of disciplines to get the insight of knowledge of other disciplines. It was achieved in two ways. The superficial boundary spanning was based on borrowing the existing knowledge of other disciplines to use as ‘tags’. The superficial boundary spanning therefore indicated the multidisciplinary character of nanoscience. The stronger boundary spanning necessitated efforts of sharing the problems, queries, expert knowledge, asking questions and interpreting the research with the perspectives of more than one discipline. It allowed the researchers to gain the knowledge of other disciplines to different extents, leading this enquiry to a domain of complex disciplinary integration which shows a greater multi-disciplinarity in general, while at the same time, some degree of inter-disciplinarity when compared with basic disciplines of science. The researchers were seen to be more comfortable with their disciplinary knowledge as they could connect it with their prior studies. As a next step, the researchers looked for different ways they could approach the new knowledge of the other disciplines. Therefore, it would not be wrong to say that scholarship of nanoscience research can create new paradigms of knowledge at the nanoscale instruments, with an emphasis on scholarly ways of boundary spanning.

Mapping of research portrayed the perceived disciplinary boundaries by the researchers and others associated with their research in the nanoscience area. Mapping introduced political challenges for researchers while researching in the nanoscience area. The misunderstandings, disagreements, expectations and false judgments were more likely under such circumstances. These mapping challenges were tackled with a few skills and competences such as decision making, initiating new research tasks, organising planning meetings, sharing responsibility of knowledge transfer in the research group, effectively communicating the disciplinary strengths to the researchers from other disciplines and time keeping. While these skills may not be unique to the researchers working in the nanoscience area, they are certainly important. The focus of overcoming the challenges arising due to mapping of disciplines was on creating a comfortable environment within which the postgraduate researchers could span the disciplinary boundaries.

Lastly, the informal teaching was observed as an inseparable part of the postgraduate researchers' life worlds. It was apparent that the informal teaching opportunities were welcomed by the researchers.

6.4 Summary

Explicating the essential themes of 'researching in the nanoscience area', it is now clear that the researchers experience this area as an experience of 'boundary spanning' and as 'a journey of mapping'. With this new understanding, I go back to my research questions and address those questions in the next chapter.

Chapter 7 Discussion and conclusions

7.1 Introduction

I begin the discussion by reiterating the central meaning of the phenomenon of ‘researching in the nanoscience area’ which emerged from the interpretation of the researchers’ lived experiences. The researchers experienced the phenomena essentially as a boundary spanning activity and also as a journey of disciplinary mapping. Further, the informal teaching, and learning by teaching in the research laboratories were central to their ‘being’. The examination of experiences could bring visibility to the researchers’ problems, issues, challenges, efforts, learning, strengths, emotions and integrity which had given the essential meanings to their life worlds as described in the previous chapter. In this concluding chapter, the spotlight of the discussion is on the new meaning of the researchers experiences, or in other words, understanding of the phenomenon ‘researching in nanoscience area’ which emerged from this hermeneutic interpretive phenomenological study.

My first research question in the thesis was the following.

- **How can the disciplinarity associated with nanoscience be defined?**

By examining the researchers’ lived experiences, a better insight into how they perceive and understand nanoscience has been gained. This understanding address the challenges associated with defining the disciplinarity of nanoscience. Three dimensions which characterise the cognitive disciplinarity of nanoscience, as experienced by the researchers working in this area, are presented in this chapter.

The second research question in the thesis was the following.

- **What core knowledge, skills and competences are necessary to successfully research in the nanoscience area?**

The examination of the researchers' experiences identified knowledge base, skills and competences the researchers have applied to successfully work in this area. Therefore, it offers a deeper understanding of the attributes which are considered important/necessary by the researchers themselves in their life worlds. In the phenomenological tradition, this newer understanding of the phenomenon by itself is an important accomplishment of this hermeneutic interpretive phenomenological research.

7.2 Cognitive disciplinarity as a newer approach

Ever since nanoscience research started, the researchers have applied scientometric approaches to determine its disciplinarity [Eto 2003; Repko 2006; Porter and Youtie 2009]. As discussed in section 2.3, although the scientometric approaches have been important, they did not address the cognitive disciplinarity. Therefore, the labels 'interdisciplinary' or 'multidisciplinary' or 'separate discipline' fixed to this area as a result of scientometric studies did not define its disciplinarity in a complete sense. The cognitive aspects of disciplinarity are understood more clearly through the exploration of the cognitive worlds of researchers.

The task of defining the disciplinarity of nanoscience has been complex and challenging. From my interpretation of the researchers' experiences, it is clear that a single label of 'multidisciplinary' or 'interdisciplinary' or 'separate discipline' cannot be fixed to this research area. In other words, it is not possible to discuss the disciplinarity associated with nanoscience solely as being 'multidisciplinary' or 'interdisciplinary' or as a 'separate discipline'. An alternative way of describing the cognitive disciplinarity is as one whose foundation is characterised by three new dimensions emerged from this hermeneutic phenomenological study. The three new dimensions of cognitive disciplinarity of nanoscience are explained in the section 7.2.1 below.

7.2.1 Three dimensions of cognitive disciplinarity of nanoscience

The cognitive disciplinarity as experienced by the researchers was neither entirely multidisciplinary nor interdisciplinary, as it takes some aspects from both of these perspectives. However, importantly, this complex disciplinary integration does not lead to an end of distinct core disciplines at any time as the researchers could not detach themselves from their core disciplines and perceived themselves as 'disciplinary graduates' first with the skills to research at the nanoscale. Furthermore, the researchers also perceived that their views, logic and thinking were understood better by colleagues from the same disciplines. The researchers gave many examples (discussed in subsections of 5.3) describing their experiences of 'judging or getting judged' on many occasions by colleagues, supervisors, reviewers, editors and collaborators from other scientific disciplines which resulted tensions, challenges and dissatisfaction. The nanoscale instruments and nanomaterial further allowed for opportunities of boundary spanning where researchers learned to build connections between the disciplines. Such boundary spanning therefore initiated the researchers to think beyond their own disciplines and connect with the knowledge of other disciplines to some extent. These connections however were made at different levels ranging from superficial to deep.

Many researchers nodded on the 'broad' nature of nanoscience and commented to know 'very little' of all scientific disciplines if they had to consider that all disciplines were merged together as a separate nanoscience discipline. They perceived the knowledge of their own discipline as important in the first place and described it as ‘essence’ or ‘expert knowledge’ or ‘fundamental blocks’. Further, although many of the researchers articulated the challenges when their research involved knowledge of multiple disciplines, they considered themselves overall as ‘successful’ researchers. Therefore, in a holistic view, nanoscience was not perceived as an ‘entirely separate’ or ‘specialized’ discipline on its own. Instead, researchers perceived disciplinary boundaries and considered their core disciplines important. In addition, they claimed ‘something extra’ was needed to connect with the other disciplines. The interpretation therefore reflected that the researchers perceived that they did not have to be experts in all scientific disciplines in order to become successful in this area. However, they needed to span the boundaries to pick the right knowledge, information, or the right people/resources from other disciplines that can assist in the research, and finally integrate such knowledge in their own research. In such situations they needed an ability to understand the commonalities of mutual disciplines, gain multiple perspectives, and integrate those in the research. Thus, researchers interested in boundary spanning needed to find ways to collaborate with researchers outside their disciplines. Although the institutional infrastructure provided researchers such opportunities at times, the researchers needed to explore cognitive collaboration with researchers from other disciplines by adapting meaningful ways of communication. Such cognitive collaboration within different disciplines was although limited in a narrow context of their research. Therefore, boundary spanning therefore breaks the disciplinary silos & takes up activities between extreme disciplinairian’s and extreme interdisciplinarian’s view and gives newer dimensions of cognitive disciplinarity of the nanoscience area.

Altogether, the cognitive disciplinarity associated with the nanoscience area was characterised with three new dimensions as listed below.

- First dimension- Nanoscience did not claim to create an entirely new or separate discipline.

- Second dimension- In spite of the integration of scientific disciplines, the importance of the core disciplines was still valued and appreciated by the researchers in the nanoscience area.

- Third dimension- In some sense, the nanoscience research diminished the 'sense of identity' of the distinct disciplines by introducing new opportunities for working across, between and beyond the disciplines. This process of diminishing or loosening up the sense of disciplinary identity nurtured the boundary spanning skills.

7.2.2 Boundary spanning skills and nanoscience disciplinarity

The researchers bring their own disciplinary knowledge and skills in nanoscience research. In addition, they also act as 'boundary spanners' to cross their disciplines when necessary. As discussed briefly in the previous chapter, boundary spanning was achieved by the researchers in a few different ways. In superficial ways, the knowledge from other disciplines was 'borrowed' by trusting the resources and knowledge. Such boundary spanning involved accessing the information which was readily sourced from colleagues. Superficial boundary spanning was particularly adapted when the researchers could not share their thought worlds with researchers from other disciplines (or did not consider it important). While in other cases, researchers achieved the boundary spanning locally by word-nets, exploratory words, diagrams and images or a common vocabulary. This increased the possibilities of researchers being able to interact with other researchers and make use of their expert knowledge constructively.

The researchers perceived that a social comfort was needed to share, discuss and clarify problems. As discussed earlier in section 6.2.1.3, experts in the nanoscience area have also emphasized the development a work environment where the researchers could ask the simplest possible questions to their colleagues. Therefore, it is clear that for stronger boundary spanning, fostering the interactions between postgraduate researchers and a social comfort is important. The networking of the postgraduate researchers on platforms such as discussion forums, seminars or workshops can be beneficial in this context. Such efforts can encourage the researchers to develop the abilities required to present simplified versions of their research to the 'non-specialist' audiences. Such explanation skills are focused on simplifying the theories and processes across the discipline rather than explicitly giving one's own ideas or views.

Boundary spanning was also achieved by acknowledging the importance of knowledge from each contributing discipline and at the same time asking questions and more explanations for greater understanding of research. The researchers in this case were interested in understanding their research through the window of different disciplinary perspectives stressed on sharing their views, their informed opinions and arguments with other researchers. They enhanced their own understanding of the research by reviewing the other disciplinary perspectives and synthesised this new knowledge into their research. The researchers asked queries when they were not convinced about the new knowledge produced. They linked the new knowledge as a combination of both perspectives. However, they commented that such new knowledge was specific to their research projects. The researchers did not claim to know everything about the other involved disciplines as their efforts were concentrated on project specific learning. The researchers also considered themselves responsible for synthesizing, communicating and teaching such new knowledge to others. While diminishing the sense of disciplinary identity, such boundary spanning also initiated the postgraduate researchers to play different roles such as knowledge producer, communicator, trainer, manager and arbiter in nanoscience.

My intention in this research was neither to criticise nor to advocate any particular way of boundary spanning as a 'good' or 'bad' way. The researchers perceived their own way of boundary spanning as the key to becoming 'successful' in their research. My efforts were concentrated on bringing out a clear picture of how the postgraduate researchers perceive and understand nanoscience research by interpreting their lived experiences. Therefore I avoid the argument of 'good' or 'bad' here.

7.2.3 Nurturing the core disciplinary knowledge and boundary spanning

The three new dimensions of cognitive disciplinarity discussed how the researchers valued core disciplines. They were also willing to explore new opportunities for working between and beyond the disciplines. With the three new dimensions of cognitive disciplinarity, it is apparent that in the nanoscience area, it is not expected that the researchers from one discipline have the knowledge and understanding from all relevant disciplines. However, the researchers must have confidence in their own disciplinary knowledge and research abilities. As Breckler emphasized *"It is necessary to recognize, nurture, support and celebrate the basic disciplines* [Breckler 2005]".

It is equally true that the researchers cannot remain too dogmatic about their disciplines and should be open for synthesising new knowledge by welcoming the other disciplinary perspectives when necessary. They should develop a clear understanding of what the strengths of their discipline are and how they can be resourceful to other disciplines. Therefore, to research in the nanoscience area, what is important additionally is that the researchers learn about:

i) Commonalities between the disciplines in context to their research

ii) How they can work with researchers from the other disciplines to synthesise a newer understanding.

As a result, it can be highlighted that the academic curricula and training programmes for nanoscience should emphasize strengthening core skills in addition to nurturing boundary spanning skills.

7.3 Attributes necessary for researching in the nanoscience area

In the previous section, I discussed the three new dimensions of the cognitive disciplinarity that emerged from this hermeneutic phenomenological study. The discussion already informed my second research questions to a great extent by introducing the boundary spanning and the associated skills. Turning towards the essential meanings of the experiences once again, I addressed my second research questions here to give a voice to the other skills and competences that researchers use.

From the examination of researchers' experiences it is clear that nanoscience researchers have an affinity for their core disciplines and they also saw the potential possibilities of working between and beyond the disciplines. The researchers did not claim that they needed to become experts in every discipline or gain knowledge of all constituting scientific disciplines. Rather, they believed that project specific knowledge from other discipline/s was adequate. The project specific knowledge included learning about the concepts, protocols, methods and instruments in order to achieve their research objective/s.

The examination of experiences identified the skills and competences the researchers applied/recommended to gain such project specific knowledge. Although the skills and competences cannot be generalised for all the researchers, the attributes discussed below were repeatedly emerging in the interpretation of the experiences.

7.3.1 Mobilizing communication for the 'non-specific' audience

In order to achieve boundary spanning, direct communication between the researchers and research colleagues, supervisors/mentors and collaborators played a central role in introducing and/or mediating the disciplinary perspectives, ideas or protocols. The communication was through informal talks, discussions, meetings, conferences and occasionally through emails. Mobilizing communication was the skill of conveying the views, arguments or explanations of the specific disciplinary methods to others such that they could be easily understood by others. The researchers developed this skills at conferences, during group meetings and while discussing and planning the research with colleagues from other disciplines.

7.3.2 Decision making and taking initiatives

The researchers dealt with information, knowledge and people from more than one scientific discipline. They had to take responsibility for knowledge of their core discipline and construct new project specific knowledge at the cross section of multiple disciplines. In this process, they were guided by colleagues who were experts in only one of the contributing disciplines many a times, however the researchers were 'spokesman' of their project specific knowledge involving multiple disciplines.

Therefore, the researchers had to understand the knowledge relevant to their project from other disciplines and plan their research. The decision making skills emerged as important skill in the research planning as the researchers proposed ideas, analysed research findings and took all the decisions related to the further course of action in their research. The decision making skills also enhanced researchers' motivation to explore innovative ideas and establish new collaboration.

The researchers shared the responsibility for knowledge transfer in the research group in order to keep the group updated about their research contributions. When working in the large research group involving researchers from multiple disciplines, they expressed the importance of effectively communicating the disciplinary strengths and weaknesses and commented that it can reduce the possibilities of judging/mapping their performance by other researchers.

The researchers also articulated the importance of time keeping, communication skills and research writing skills in general. They discussed about critical thinking skills which involved developing a questioning attitude to gather knowledge, analyse results and recognise problems areas, and covey the results precisely. Many of these skills and competences could be argued as desirable for a researcher from any scientific discipline.

7.4 Guidelines or recommendations for the curriculum development and training programmes

The preceding discussion extended knowledge of the cognitive disciplinarity associated with nanoscience by describing the three new dimensions which emerged from the hermeneutic phenomenological examination. This examination also identified the attributes that researchers use to research successfully in this area. This newer perspective of nanoscience research obtained through the hermeneutic phenomenological examination provided three recommendations for the curriculum development and training in this research area.

7.4.1 Networking different disciplines at undergraduate research projects

As indicated from this research, the researchers working in the nanoscience area must have confidence in their core disciplinary knowledge and research abilities. Further, they required boundary spanning skills when necessary. Nurturing core knowledge and boundary spanning skills can be aimed right from undergraduate education. The undergraduate curricula should firstly aim to develop the core disciplinary knowledge. Further they should provide more opportunities to develop boundary spanning skills to the students.

Science education at undergraduate level has been dominated by disciplinary silos [BIO 2010, National Academies Press 2003]. It leaves little room for networking undergraduate students to work together or to gain the boundary spanning experiences. The first step to prepare a workforce for the nanoscience area can be initiated by creating opportunities to make connections between these disciplinary silos by reconsidering the final year undergraduate research projects. The undergraduate research projects could be structured for a network of small groups of students from the different scientific and engineering disciplines. The research project could have a main research goal that is achieved by the contribution of all the involved disciplines.

It was also evident that the researchers invest significant amount of time on learning and getting hands on experience the nanoscale instruments. Hence, an early exposure to the nanoscale instruments through the undergraduate research projects could be beneficial. Such projects can encourage the students to bring their own disciplinary skills into action and in addition it can promote the boundary spanning communication in order to accomplish the broader research goal. Through such projects, the students should develop the skills required to contribute in their own discipline while also learning to work together and developing an understanding of what is common to all the disciplines.

The students should be encouraged to discuss and reflect on their experiences which can bring a sense of what needs to be focussed on in the research meetings and why. Such projects could amplify students' learning in their own disciplines by enhancing the sense of understanding of what their core discipline can offer in the research. Additionally they learn to work together as students from different disciplines and bring different knowledge base and different world-views.

7.4.2 Providing opportunities to reflect on research experiences

The experience of mapping was recollected through many stories. Such mapping had both a positive and negative influence on the researchers. In a positive sense, it made them more responsible, aware and engaged them in multiple roles such as manager, communicator, knowledge producer, research initiator and arbiter thus preparing a ground for their professional roles in this area in the future. With respect to the negative influence, mapping occasionally resulted in feeling 'disconnected' from the broader research goals and 'intellectually deserted' or 'being neglected' in the research group. When the stories were viewed holistically, it became clear that researchers did not have many opportunities to reflect on their experiences and share these reflections with others in the working environment. The lack of reflective space could affect their enthusiasm and hinder their progress and involvement in the research overall.

Developing a self-reflecting practice could encourage the researchers to take a moment to think about their own experiences. Such practise can connect them back to their research positively by visualising the problem areas in their research. Furthermore, providing a common platform to reflect on the experiences can provide the researcher with an opportunity to open up about their challenges, issues and emotions and make others aware of it. Experts can guide the researchers to resolve their ambiguities, reduce the disparities and thereby foster an environment of positive regard. Therefore, the training programmes in the nanoscience area should familiarise the researchers to the practise of self-reflection.

7.4.3 Creating awareness of social, commercial and ethical policies

Another recommendation is in relation to awareness of social, commercial and ethical policies. From the examination of researchers' experiences, it became clear that the researchers had ambiguities regarding aims/interests of commercialization workshops, collaborations and ethical policies in this area. The researchers should be made more aware of the ethical, social and commercial issues and policies related to nanoscience through lectures or guest seminars. They should also be encouraged to think critically about these issues and policies and discuss and implement them in relation to their research project where necessary.

7.5 Quantitative survey

Before explaining the quantitative survey, it was important to confirm the credibility of this research in the qualitative domain. The hermeneutic interpretive phenomenological philosophy suggests that the credibility of the research conducted under the scholarship of this philosophy is confirmed in terms of the depth of involvement of the researcher in the inquiry [Giles 2008; Laverty 2003]. As discussed earlier in chapter 4, Van Manen suggested four criteria; orientation, strength, richness and depth, to judge the credibility of the phenomenological research. This research of examining postgraduate researchers' experiences explored the essential meanings of the phenomenon of nanoscience research. By including the decision trails and presenting the interpretive writing and analysis, I expressed my deep involvement with the research and thus confirmed the depth of this research. This exploration of phenomenon provided a deeper understanding of the very nature of nanoscience area and addressed the research questions of interest. Therefore, my orientation towards the crafted stories with the research questions in mind was successful. Further, discussing my readings, thoughts, reflections and experiences in the interpretive analysis, I demonstrated how I had taken the 'strength' criteria seriously.

When I discussed the philosophical underpinnings of the research, I had confidence in the merits of the hermeneutic phenomenological philosophy to explore the life worlds of postgraduate researchers. Furthermore, as I was more engaged in the interpretive analysis process, I appreciated the potential of hermeneutic phenomenological methodology to answer my research questions. However, I was never too rigid to neglect the critique or the limitations of the research arising from any of my decisions in the development of the research design. In relation to the interpretive nature of hermeneutic phenomenological examination, one can critique that the interpretations of the lived experiences were the researcher's own interpretation of the postgraduate researchers' lived experiences. One way to address it was by going back to the postgraduate researchers with my analysis and interpretations and having them validate my findings. I had taken the transcripts and crafted stories back to the participants for verification however discussing the interpretations with individual researchers was beyond the scope of the research within the available time frame. A short survey was developed on the basis of the key findings of the interpretive analysis and the proposed recommendations to obtain the researchers' views. The idea of a survey may appear contradictory to the theoretical and phenomenological foundations of the hermeneutic phenomenological research. I am fully aware that hermeneutic phenomenological research intends to obtain a deeper and fuller understanding of the phenomenon of 'researching in nanoscience area' and not generalizing the interpretation for a complete understanding. The quantitative survey was only to check that I have not 'surprised' the researchers with my interpretation of their experiences. The researchers' feedback collected from survey was a way to get a quantitative response for this study which can be of interest to the higher education institutes and curriculum developers.

The survey was conducted through email. It was sent to all the postgraduate researchers from my database of participants (discussed in section 4.2) including those 25 researchers whom I interviewed in the study. The survey included two main questions. In the first question, the skills and competences identified from this study were listed. The researchers were requested to rank these skills and competences in the scale of 0 (least necessary) to 5 (most necessary). The second question involved the descriptions of nanoscience as a i) separate discipline ii) multidisciplinary area iii) interdisciplinary area and iv) boundary spanning area as given in Appendix 4. The researchers' needed to select the appropriate description/s which best describe their research.

A total of 52 responses were received. The quantitative analysis of survey data indicated that 62% researchers agreed with the description of nanoscience as 'boundary spanning area'. Thus, the quantitative results were in good agreement with my interpretation of disciplinarity of nanoscience. Further, the majority of researchers ranked the following five skills as most important.

- Acknowledging the contribution of other disciplines
- Sharing research experience with colleagues
- Understanding broader goals of collaborative research
- Explaining strengths and limitations of their discipline to researchers from other disciplines
- Critical thinking skills

The triangulation of quantitative survey outcomes with the hermeneutic interpretive phenomenological research enhanced the credibility of the overall research.

7.6 Concluding remarks

There is an acceptance amongst education and research institutes of the need to address the educational challenges associated with nanoscience stemming from the complex disciplinary integration [Roco 2003]. However, to date, the studies in relation to curriculum development in the nanoscience area have focused mainly on the development of the contextual knowledge associated with this area. For instance, many studies only focused on the technical skills necessary to work in this area [Abicht, Freikamp and Schumann 2006; Bhat 2005]. There exists a scarcity of literature, and hence research studies, that focus on understanding the cognitive aspects associated with nanoscience due to its nature. Furthermore, the area has remained bound to the labels of 'multidisciplinary' or 'interdisciplinary' or 'separate discipline' based on the recommendations of scientometric studies of disciplinarity which do not necessarily cover the cognitive aspects of disciplinarity. Even then, there is not agreement in relation to how we define the disciplinarity of nanoscience. To fill this knowledge gap, a better understanding of the cognitive disciplinarity associated with nanoscience becomes necessary.

This research was set out to obtain a deeper understanding of the phenomenon of 'researching in the nanoscience area' and thereby get an insight into the cognitive disciplinarity associated with this area from examining the postgraduate researchers' lived experiences. A hermeneutic interpretive phenomenological methodology was applied to examine the researchers' experiences and hence to understand how they perceived and made a sense of nanoscience research. Choosing hermeneutic interpretive phenomenological methodology made me a 'seeker' to welcome the new and unknown meanings of their experiences and thereby understand the phenomenon of nanoscience research.

Examining researchers' experiences of nanoscience research, I understood that the researchers experienced nanoscience research essentially as a boundary spanning experience and also as a journey of mapping. The new meanings of the experiences in turn provided an insight of the cognitive aspects of disciplinarity.

Three newer dimensions that characterised the whole cognitive disciplinarity emerged. The first dimension indicated that the nanoscience research area did not exist as its own, specialized or separate discipline and the postgraduate researchers always associated their prior disciplinary practices, thinking and approach to conduct the research in this area. The second dimension indicated that the complex integration of disciplines did not lead to an end of core disciplines. Even while working in conjunction with other disciplines, the importance of the core disciplines and their knowledge base was appreciated and valued by the postgraduate researchers. The third dimension indicated that in some sense, the researchers attempted to diminish the ‘sense of identity’ of the distinct disciplines by introducing newer opportunities for working across, between and beyond the disciplines in their research. The researchers appreciated the knowledge, methods, protocols, practises of their core disciplines but they were not stagnant within disciplinary silos and welcomed newer opportunities of synthesizing knowledge by the efforts of boundary spanning.

There were a few examples of the researchers aiming for a common understanding of their research data for particular experimentation, regardless of their research discipline. On the other hand, there were many cases where researchers were involved in the same research project with different disciplinary perspectives. As a result, none of the labels (multidisciplinary, interdisciplinary or single discipline) can be attached or fixed to the research area as it displays characteristics of both multidisciplinarity and interdisciplinarity. From the examination of researchers’ experiences, the integration of both perspectives at different levels was seen as a theory in practice. Therefore, promoting any one particular approach and aiming to develop the researchers for either a multidisciplinary or interdisciplinary platform would not be appropriate. Also, the postgraduate researchers did not claim for the necessity to have knowledge from all the disciplines, although they needed the abilities to identify the commonalities of the disciplines and apply different ways of boundary spanning to integrate the knowledge in their research.

The aim of the hermeneutic interpretive phenomenological methodology, as discussed in the methodology section, was to seek the essential meanings of the phenomenon.

This study of examining the researchers' lived experiences, guided by hermeneutic phenomenological methodology, explored the essential meanings of the phenomenon of nanoscience research. It enhanced the understanding of the nature of nanoscience in a great depth. Based on the enhanced understanding of nanoscience, it has been possible to make some important recommendations for the curriculum development. It was clear that for nanoscience research the students need to strengthen their knowledge and research abilities in the core disciplines. They need not have been presented with a haphazard collection of courses from all different disciplines, however, they needed more opportunities to explain their disciplinary perspectives to others. The students needed to develop an understanding of what is 'common to all' in their undergraduate studies and learn how they can work together effectively by spanning the boundaries of different disciplines when needed.

7.7 Recommendations for future work

This research focused on examining postgraduate researchers' experiences to develop a greater understanding of nanoscience. It was not possible to address all the interesting issues which arose during the course of the research without losing focus of the research.

Although the number of participants was limited, the hermeneutic interpretive phenomenological examination provided a broader understanding of the cognitive disciplinarity of nanoscience research with its three newer dimensions. The study also indicated the importance of boundary spanning skills. A further research study could be conducted with a greater number of postgraduate researchers to understand how they apply the boundary spanning skills in their day to day research activities. The experiential accounts can be analysed further to obtain a better understanding of these practices and how such knowledge can be implemented further to develop specific assessments and learning exercises. Furthermore, although interpersonal communication emerged as a dominant tool for boundary spanning, further research could be conducted to identify if there are other ways by which researchers connect with the other disciplines in nanoscience.

Further studies could also be conducted by interviewing the postdoctoral researchers and principal investigators working in the nanoscience area to learn more about how the commonalities in the research across the discipline are understood in the group.

The experiences of postgraduate researchers who turned into professionals in nanoscience industries in their career could be studied to understand if these skills have migrated and are considered important in the workplace.

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(References are listed in ISO 690 style)

Appendix 1

Crafted stories from Alan's transcript

Building learning 'bottom to top' (Alan)

In my undergrad teaching, I had to explain common entry level science students my research in a few sessions. That was interesting because I considered them kind of a lay audience. They were biology students and they had no idea of physics what so ever after their leaving cert. To explain the audience at that level, you can't go with a package of heavy or complicated terms. I knew I can't make use of the term 'surface plasmon resonance' for them directly. If you tell that to a physicist, they are OK with that, but if you tell that to a biologist, they have no idea about it. So, I had to think for some time. I remembered how I understood quantum biology first, by splitting biology as laws of energy transfer which I was familiar with, and then I knew I have to explain undergraduate students in the same way. So, instead of giving the information from the top, I gave them building blocks to work from. So it is like building a platform where you can build complicated stories. That was something the most practical thing I learnt by explaining the subject to others and I think that was the best thing I had done to make the theory of my own project simplified.

Adopting common vocabulary (Alan)

Sometimes introducing some basic chemistry and biology would help in getting a better researcher in projects like mine. I was in a medical college for a workshop. I was sitting in a sterile room with lab coat, gloves and trying to learn some basic cell culture for the first time. In the first week, it was all French for me. But then, I made a friend who was a cell biologist. She was like a walking dictionary for me. She used to explain me the technique practically and would tell me what was its acronym but I remembered the technique only by its purpose. So, the science is not that bad, it is just the terms that appeared French. But, if we adapt to something we all can understand, my research would be a lot easier. There is another example; the biology girl in our lab, she used to talk a lot about 'lysing' the cells as her project involved some experiments like that. But, I never got what she is talking about. I have heard about similar term in physics 'aliasing' but that was something very different context. One day, she was explaining something from her research images, and used the same term. When I saw the pictures, I got to know that it means 'rupture' or breaking of the cells and spelled 'lysing' and not 'aliasing'. I remembered then word 'lysing' has relation with breaking of cells. Now when I asked her if the laser beam could break the cells, she knew what I am talking about.

Disciplinary knowledge as building blocks (Alan)

To get the antibodies on the surface is a specific chemistry. For the metal enhanced fluorescence to work, the fluorescent molecules cannot be in contact with the film surface otherwise the process will quench (shrink) film straight away. So, you build up layers of positive and negative electrolyte and on one of the negative layers you introduce the fluorescent material. So, although it is chemistry, it is not too bad. Once I knew the significance of each step, I know why we were doing it for. I get an understanding of it in physics stand point. The actual chemistry, what is going on between them is not entirely relevant for me; I just need to know that positive and negative electrolyte layers allow the fluorescent molecules to stay apart from film; and I can build these electrolyte layers on top of each other. So, whenever I am having problems with Chemistry or Biology, if I don't know what it is, I will approach it in physics point. In antibody and surface case, I approached it form my discipline and understand what is happening there physically. When I am dealing with cells, if I have to know about cell death, I can get to see it as fluorescence results. For me, cell is like a bag full of particles, I am interested in what is happening to those particles physically. I believe that I should approach the things from the stand point where I have mastery in, but I should also know at least the point of view of other discipline to explain it.

Being there when needed (Alan)

We have two postdocs and three researchers in our group. Our PI (principal investigator) has five different projects running at the moment. She is very busy generally and meets me once in a month with all other postgraduate researchers. But, the postdocs sit with us, I can often talk with them. The perspectives they sometimes give is different, you even wouldn't think of it on your own. One of them is biologist and other is a chemist, and they look at the problems very differently which is very useful. Myself and Amanda were interested in using some biological assay for a test. I am a physicist and she is chemist. So, we were trying to reach to all the tiny details of it. But, Siobhan heard our discussion and said, 'No, you just need to do this as a standard practise. You don't need to go in the nut shells of it. It is just two simple step procedure and it is a standard protocol. No need to reinvent the wheel' I think, we were too much worrying about the test and going into details of it. But for Siobhan, it was far simpler than we were making it out to be. So, it was just the input from her that it is a standard technique used in biology all the time. It saved our few days task. Her presence at that time mattered a lot to me otherwise I would have spent days working on it.

Appendix 2

Crafted Stories of participants

Not all instruments are central (Anna)

I have done characterisation of the nanoparticles in different cell media to see if they are interacting with cell media and depleting the nutrients that is contributing to the cell death. I have used DLS, UV-Vis, SEM and AFM techniques. We do DLS analysis to determine particle size and hydrodynamic radius. We also did UV visible spectroscopy to see if the particles are interacting with nanoparticles. We have also used confocal microscopy, SEM and AFM in my project. One of my supervisors trained me how to use DLS and UV visible spectroscopy. A technician in the institute did SEM and AFM handling and gave the images to me. I had to prepare the samples and put that on the silicon wafers for these tests. I handed over that to the technician for observations. My supervisor AAA did the confocal part for me for the first time but he trained me on that. I don't think AFM is essential for me. To learn how to use these techniques is not central to my research. I use AFM and SEM, but very rarely, I mean once in a while for characterisation when I start with fresh set of nanoparticles. I would do the DLS by myself and other than that I had to do many biological assays. These biology tests are essence of my work. SEM is used to see the actual nanoparticles and see if different bile- acids are coating the nanoparticles. And if yes, then to what extent they have affected the size of nanoparticles.

AFM (Ronan)

AFM was the most tedious machine to work with. AFM tips are very delicate and putting that in the tiny slots appropriately was a challenge. When I started working on AFM setup, I had lost about a dozens of tips in the first week. They are very small and delicate. Actually, I had never been told about how awkward and fiddly AFM set up was. I have a friend in biology department, she had told me once that she has used AFM, but, when I started working on it, I realized that she must have obtained images using AFM, I don't think she had used that. It is obviously grand when somebody has set it up for you. The set- up itself was complicated. I had to check 12 different arrangements before we start up. One of the postdocs in our lab went through the basics of it with me. Initially I used to watch him working. But the problem with that it never teaches you anything. When I started working with the machine on my own that was a totally different experience. I had to play around with all different settings. The postdoc monitored me just to make sure that I do not cross the highest limits set by the system. I was trying around all different settings under his guideline, till I was confident to use it on my own. We had been taught about what is SEM and TEM in theory but the practical experience in any of those techniques would have been incredibly useful. It was really the hands on experience that was needed there. I have data with TEM machine as well, but then I had given samples to the technicians; they set it up and gave the pictures and data back, so I won't say that I have learnt TEM as

AFM. I have also used fluorescence microscopy but that is not in the same league of SEM, AFM or TEM. AFM gives a 3D image. So, interpretation was simple, I was interested particularly in knowing the time period and amplitude of the gratings by tracking pixel positions. My samples were very robust, so there was a possibility that they can damage the sample. So, I have to do it carefully. So, the main skill was operating AFM than the interpretation of the data in my work.

Identifying self (Alana)

I was already involved in using the characterisation tools, in the first semester of PhD itself. So, it kind of kicked off and started my PhD straight away. It saved a lot of time. I was already involved in using the tools such as AFM and SEM. Actually, I was introduced to them in the second year during the work placement, but then it was more theoretical. The work placement was of small duration so I could not use them although; I was introduced to the physics of tools in the second year. In the final year project, I worked with some of the tools. Ross helped me in the lab when I started. So, in the hands on session, I could apply the knowledge from theory. I kind of had a good understanding and background of what the machine does. So, I didn't have to worry any more about learning them from the beginning. I did not have to invest extra time to think where to start with in my project. So, it got me started straight away and made me to appear smarter than others. When I see other postgraduate researchers in the lab; or according to my progress so far, I feel I am ahead of them. I am already producing data and results, and results are good for publication. I am about to start writing a paper and will be having a journal publication in the beginning of second year. It has not been done in my lab so far. It puts me at another level. I feel like doing much more. My supervisor last month asked me if I would be interested in writing a student grant to hire undergraduate student for internship. It was a moment of pride for me I felt that they trusts my capabilities now. It feels good.

Sharing and questioning information (Ciaran)

I believe that the basic knowledge of the techniques being used is very important. People think 'instrumentation is a pointing shoot or place to start with' but you cannot use instrument fully if you don't understand it. When I started this research I used to ask questions, 'why did you do that?', or 'how does it work?' Sometimes people would say, 'this is how you do, and you will get the results!' Some just accept it but I believe that it will be without a real depth or understanding. I also went to work [as engineer] in XXX company dealing with computer chip manufacturing. There as well I used to ask, 'why would you do so?' at some occasions. But then, sometimes I would get a response 'well this is what you pretty much do!' They were all technicians I was dealing with. I can understand if a technician says so but as a researcher it is hard to listen to such dry responses. From the sense of research work the depth is a value. For example, we sometimes get XPS of samples done from XXX university as we cannot do it here, the report that are sent back to us are just some times attached without actually *questioning 'if this is done correctly or not?' by some people. Because the analyst might not be familiar with the chemistry we are involved with, it can create problem, so we need to show awareness for that and raise a query. I had a problem just a few months ago; we had an analyst from XXX University who did XPS analysis of my samples. I knew from other chemical technique FTIR that there was a particular chemical structure in the samples that should have been shown up through XPS, but then, this analyst from XXXX had said that there is nothing particular like that there in the XPS result. I exchanged few mails to dig the ground further. Also, I had relevant software here, so using that I was able to figure it out. Because I had knowledge of other techniques and I raised the query, I think, I could get to the root of the problem. I mean, also, because I knew in depth how things work, it occurred me; otherwise all others just accepted that as it is! The analyst was not particularly familiar with the chemistry I was using. It is very difficult. When you get a symmetric peak, for her, it was just one chemical there, but, you have to take into account different spin states of elements. So, it is a symmetric peak but if the FWHM (full width half maxima) falls above a particular value, then there must be another peak in there. She was interpreting it as one chemical bond as it was symmetric. I know that they don't deal with the spin etc. that much in chemistry, but my physics knowledge of FWHM theory was there to use right at the place and I knew that there should be two peaks. So, it was a different interpretation at the first place than I thought.*

Multiple disciplines at the instruments (Ruth)

There are a lot of new and vivid things involved when it came to learning about plasmas. The physicists in the big cluster are mainly involved in testing properties of plasmas. My work is more applied. I am lucky enough that the research cluster has a good mix of people of all disciplines. There are four physics postgraduate researchers working on plasma system, an organic chemist, a biologist and a technician in the group. The plasma systems are included in the common facility which I share with other four researchers. There are a lot of interactions between us initiated by all of us anytime. Although the physicists' interest is different, they are interested more in studying pure plasma and properties of the plasmas whereas I am interested in using the plasma system to develop my application (specific film/surface). They do not have great interest in what I am doing with the films afterwards, but they are great help to me in designing my experiments in the plasma chamber. They are experts in physics and (they) tell me all possible knowledge of settings I could use to get stable plasma each time in preparing the surfaces. My research work is situated in all physics, chemistry and biology. The organic chemist and biologist showed me the standard chemical linkers with specific carboxylic groups that could use for surface forming. There is a specific type of a linker which will bind on to only those groups. We need to find a specific spot on the surface where protein binds. It is a completely different skills set, completely biology and chemistry based. I can't fully perform the assay tests that biologists are doing, but I learnt the first linking step from where they start further tests. Having even known that, I could do preliminary testing on my own. The organic *chemist actually sat with me and showed all the chemicals and explained the actual reactions happening between them. He told me all the necessary techniques and why it was important to do. There were people who just told me, 'It is simple and we do it every other week'. But the chemist actually showed me it. Anyone can be told to mix the chemicals and just borrow the standard protocol, but it was good to have them to show me all details. They were experts for me in that area. The final product what they were interested was very different, but having even known the first step they start up with was important for me. I could test the surfaces in 100 different ways physically, but the one test from other discipline which is close to where they start their work with was very useful for me. It was handy to have people like these from all different backgrounds. When I did my transfer examination, I wanted to know the complete picture of my research, how it was used in other disciplines. So I asked biologist how they wanted to use my plasma deposited films/surfaces. It was important knowledge for me as I could do small adjustments which were beneficial for them. Learning some of the biological tests by myself, I could adopt the knowledge by which I could understand what they are interested in. Also, once the biologist came back with some problems about the films, I could argue with him with this understanding.*

Sharing knowledge world (Michael)

I was working with the Masters student; it was kind of a team of us. We both were new to the area so exploring this area more was fun. We had to coordinate with each other regarding the depositions, parameters and the characterization of the coatings. I was kind of teaching him and helping him to build his understanding of the system better, I knew how different parameters have effect on the coating I worked earlier on, but then, I was also new to these set of coatings, so, when we look at the developed coatings, we both used to discuss the results, we would discuss how we can improve them, So, it was like we were helping each other but also working for a common thing. We used to ask each other questions all the time and check each other's opinion and make sure that we both we understand the same thing. In a way it helped me to build my understanding of the technique more confidently. We also then looked at the protein interactions with these surfaces or coatings. That was a new technique, I have not learnt before. So the project was very good for me and I enjoyed working with him. Also, I got a research paper out of it and the guy received his master degree. A lot of that work is going in my thesis as well.

Transparency about publishing research (Sean)

The company expected some work in turn of the funding provided. That part of research is going into my experimental chapter of thesis. But the problem is that, they don't want me to publish this research in the journal papers. There were two good papers that I would have published through that, in academic field you require to have research papers published. Even though the company is very helpful, they are great people to work with, but, you can't publish the research, which is frustrating. And even *more frustrating is that, I was not aware of it while I was working on it, I just came to know after I finished a significant part of work. I had invested a lot of time in it, and I was quite successful in terms of achieving the goals what they were expecting from us. I was frustrated. But then, I could just talk about it. When I had a meeting with personnel in the company, he asked me about 'when can I complete the particular work for them' and I mentioned that 'I was pretty much busy with other aspects of the research'. The person explained to me that, 'with the funding received by the company, I should prioritise my work for them first', but then, I had to explain to them with due respect that, it is equally important for me to publish the papers and this work is not taking me there in any ways, so I had to slow down and focus on other things simultaneously. So that was one incidence. I was frustrated but you cannot do anything because they are also providing funding for my research. If they had explained it to me right in the beginning that if your work becomes successful you won't be able to publish that. When I started my PhD, I didn't understand the importance of the research publications but, I feel like they should have explained it to me. Also, the company should have been told by the academician about the importance of research publications. If I would have the idea about it beforehand, I would not have been disturbed about it. I would have thought about other ways of obtaining research publications. So, a lot more transparency at the start is important.*

Judging work from lenses of other discipline (Ciaran)

Within the mechanical engineering school we have three different groups working together. We are doing different things which coordinate in some or the other way to the main frame research. We are preparing the samples [nanoscale coating] and the other group is doing cell biology work on it. There are issues with the ownership of the paper sometimes. I had worked on the XXX sample for a hell lot of time and I was not convinced to have second authorship. Although, the work was more biology based but, looking at the time I have spent in preparing these coating, I was not convinced for a second authorship. Finally it went down to two different publications in different journals. Now, situation was ok because it was sorted out differently, but the problem would not have been so much if it would have been discussed at the very beginning. Now, it was all OK in the beginning, but, once biology group noticed good results from coatings, they wanted to have then. So finally, I and my supervisor had to go to them and talk in detail. The person whom I was working with was a medical doctor. We had to sit down and literally work out the list of things we decided to do initially and things we actually offered them. Since I was doing lot of coatings, even a lot of protein related stuffs, we had to decide who is offering what in the paper and based on that who should get what (rank) in the authorship. So, that was the case with one of the collaboration, but we had to take a clear stand. Now, in their perspective, the coating was not that time consuming as the other biology work was, so there were issues with the authorship. But then, my supervisor took initiative and explained the experimental background work needed to achieve the coatings. Actually, later on, the background work also came up as a second paper, but we had to convince them for the first *paper…. You need to specify clearly that this is the work I will be bringing in the study from my side, so, I would be given first or second authorship. The line should be drawn very clearly from the start otherwise it can make postgrads annoyed as we are the one who are suffered in the process. Ownership should be specified very clearly. In my group, my supervisor DDDD would say during a meeting that such XXX person is looking for this, it is very casual approach at the start, I had even found myself doing work without anybody have not discussed much about it just because DDDD has asked me to do that, but at the time of publication, people get annoyed. I know the last time, when we did a collaborative work, fortunately I was down in the publication, but I know a few postgrads within my group, they worked for it but were dropped from the paper later on by DDDD. It was not fair. So it is very important to discuss, at least I would say from my own experience. Now people sometimes in the start-up time would not see that it could go for a publication, but then things can change. It is true for any work that involves such collaboration of few groups from different disciplines, but it is there in nanoscience area more obviously. It is hard to judge which part of work in the collaboration is more important. It is hard to judge the results of other disciplines with the same lenses. I had met people in conferences and workshops and heard similar stories from them.*

Sense of responsibility (Michael)

In the area I am researching in, it is extremely important to have research publications. It is a comparatively new area with growing research community and people would know each other mainly through the publications. Publications are important to make my own identity in this area. Well, research publications are important in the PhD in general, but other fields of research are kind of saturated. After all, we can impress people only be digging some new thing. Nanotechnology research is still forming its roots on our research. There are many things happening at nanoscale that as a researcher we are not aware of. We are still finding the answers for it. We are fortunate that we have this area to explore and make our mark carrying a sensible responsibility on our shoulders.'

Dealing with the expectations (Adam)

The plasma systems are used to create polymer films in my project. The idea is to get specific chemical layers by reforming chemical layers using controlled plasma processes. These specific layers can be used in the biological assay development. The larger research cluster is interested in these assays as it allows sticking the specific biological targets on their surface. My supervisor SSS is from engineering discipline so I have engineering side but I work with the group members involved in biomedical research. My supervisor has a very specific side of getting the engineering into the systems. The plasma systems we work with are very expensive but fantastic and well suited for the task. We are always behind getting the recipes for depositing these films in right way and calculating the percentage errors when we are developing different *thickness of these layers. Plasma systems have large room for errors and even a small change in parameter affects the layers. These are very small, nanoscale layers only about 5nm. Even to standardize one recipe and show that they are reproducible in same way is a major work, almost equivalent to one PhD in engineering discipline. Whereas, the biomedical part of our cluster just want the layers as they allow sticking the specific biological targets. They wanted as many types of specific layers as I can produce in my PhD. So it is the different end products we are interested in and I am stuck in between both of them. I am more interested in varying and observing different parameters in the plasma systems and test how they effect on the coating or films. The biomedical group just want different types of films that can serve their purpose. If I tell the thing to my colleagues working on plasma systems they can completely understand my situation. They know how difficult the reproducibility of such layers was. But nobody in this group can understand this if I tell them that I need to spend a lot of time in getting the plasma system working right for my samples. They do not have idea of its complexity and were expecting me to come up with 3 or 4 different type of layers. I prefer going to my engineering supervisor to discuss the work when it is just between two of use. The biomedical group meetings are more frequent but I attend those once in a while. Honestly, there is not much interesting interactions for me at that place. Those are planning meetings to discuss our broader or long term goals. I need to attend that as I report my other supervisor from biomedical group about my progress in that meeting. I had to negotiate with him about the time required to produce the layers. He has a few students working with these layers further on. But SSS's remarks are more important for me as far as my research is concerned.*

Constructing results and perspectives of disciplines (Anna)

There were some DLS results I had to present. We had the nanoparticles suspended in different solutions such as water, cell-media, cell-media with particular bio-fluids such as bile-acids. My supervisor DDD from physics wanted to present these results in a specific way to show their distribution in size. The DLS results we get normally will be in form of numbers. I did not know how to present these results particularly. It was DDD's idea to present it in form of graphs. Although, I had seen how others presented the DLS results in our nano-group before, but it was mainly for one type of nanoparticles and the media. I wanted to do a comparison of different solutions. DDD suggested the idea of principle component analysis. It was very different way of presenting it that I could not think of. I was so used to do the toxicity and assay study that it did not occur to me easily that how I would show the nanoparticle distribution results in graph of multiple variables. I was comfortable in presenting the toxicity assay study with two variables. But DDD gave me this idea to present DLS results in this form. We all are from different disciplines and brought different perspective in the research. His expertise in physics made results look concise and more presentable.

Politics of research (Amanda)

Industrial collaboration has affected my work all the way through my PhD. Sometimes, I don't have a choice. These samples on my desk are biomaterial samples from some companies. If I would have a choice, I would tell them that the particular chemistry XXXX will give better results. But companies come to us with some samples and I had to just test the samples without any creativity. From the fundamental understanding point of view it is difficult to communicate to them. They just want the test results and if they want it only that way, I do it. Such type of work used to irritate me earlier as it takes up my time! This company is probably the 12th I am testing samples for!! The longest that I have spent on such work is about six months. It is good bit of dedicated time and work. The company would come to us and ask if we could do some preliminary tests, I will probably try and work to get the best solution, but then, sometimes they never come back to us afterwards for any kind of knowledge transfer. So, all the work invested on them in research point of view will be in vain… Eventually, I thought that such work is not going to award me with the degree if I do things other than testing for them. Now, I try to do the minimum for them, that too as fast as possible… There is lack of motivation in my part for industry involvement in the research, as I have not seen any common goal. Although my supervisor said that perhaps one in ten companies might get back to us and fund our research. Sometimes, companies would have funds that they have to utilise for research, for different purpose such as tax exemption. But then, they come to us anyways. My supervisor also likes to approach different companies for research. I think that is his goal. But then, there is other side. This sample is of XXX company; I would like to apply there for a job at a certain stage. My work helps to have that connection at some level. I would like to mention at some stage in the interview that 'I have done such coatings for you'. I think, it adds in to my experience.

Communicating 'what' matters! (Olan)

Nanotechnology conferences are same as a group of college friends or football team where you get a mixture of people. The area is so broad that many research conferences can be included under this title. The bigger conferences are better to participate as you get to meet more people from different parts of research in the big circle of nanoscience. I had been to nanomaterial conference in XXX. It was very big, but inside it were little sections. Even I found one specific to nanowires I am researching on. There were other sections on solar cells, battery materials, grapheme, thin films, lithography and all. In terms of communication, as there are vast many groups, there are lot of different styles of presentation of people. There is not one set or uniform way of presenting. You get to listen to a lot of different types of talks; some might use many slides and some use figures. The way I communicated in such conference was, I do use some technical details, because obviously people will know what is current research in that area, but by doing that I would also give lot of emphasis on explaining 'what you are doing and why you are doing that'. I include my *thoughts on the ways the research can be useful to others, That was important part as it helped people who were not exactly in that field to understand what the research was about. If you are explaining a detailed reaction mechanism where someone has no interest in, but, if they know what the end product is and what it can offer, they can think about its usefulness for their own research. So in certain conferences, I preferred spending more time on motivation of my research. It is like more than communicating how, it is also necessary to know communicating what in this area.*

Bringing equal responsibility (Mick)

I am familiar with the rates equations in general. But the mathematical equations now I am dealing are modified on the grounds of rate equation and needs some biochemistry knowledge. I know it to a certain stage. In the research we try to explain the mathematical equations with the biochemical processes happening in cell. My supervisor FFF can look into the problem in a very mathematical way as his background is mainly physics, whereas, I kind of look into the result in a more biology perspective. FFF would look at the result of the equation and try to jump for conclusion in a very analytical way. But then, I have to say to him 'Listen, you know in a living cell that does not really happen!' I have to explain biology to him. For us, we were using the uptake of nanoparticles as a parameter and looking at it as a rate in mathematical term. It is a general thing for a physicist, but then, when we interpreted the output of the mathematical equation, I can bring biology into it and see if the result is justified biologically first ... I try to incorporate my knowledge of biology in explaining what process is possible behind the mathematical equations. With by biochemistry background it is handy. I am able to know what happens in the cell and then looking at the equations I can judge if that really work with what I know that happens inside the cell biologically, when nanoparticles are taken up. So, it is good to have a reference of cellular mechanics learnt in biochemistry. Sometimes, I see sometimes extremely different values when we run the code with the mathematical equations. It can be an error in the experimental data or the incorrect initial values, or even something else. But FFF took it as the cell behaviour under such situation which is an error! So I needed to clarify that. I feel I am involved in biology aspect of knowledge although the project involves mathematical equations and modelling. Sometimes, when talking to HHHH, I have to explain my understanding in more detail to him. I cannot assume that he will be familiar with all the terms in cell biology, and neither can he! So, I need to prepare myself more in biology first for him and should make him understand what I mean at different contexts during the research. I feel it is my responsibility. Also, he has to do the same for mathematics. Like, one day, he was trying to explain me some differential equations and how we can add limits to the equation. He just went through all process in a minute and I was like blank staring at him! I had to remind him sometimes to go slow and ask for easy explanation.

Working together (Damian)

The postdoctoral researchers and my immediate seniors helped me in arranging the experimental set-up. It was much easier communicating to them as we all were thinking in similar ways. Many of us had physics background. They picked up biology related to our experiments in a similar way as I did. With MMM (supervisor), I could talk to him about the biology aspect as that is his background. He never minded answering my questions, even a stupid question in biology But, when it came to designing the set-up or more fundamental part of optics it was different. I mean, he never came across such polarization sensitive device in his research, so he was not of much use to me to discuss what specifications I should be looking for when I am ordering them. He could not help me out with the optics part in designing the set-up but I didn't mind it at all. He wanted me to take the ordering decision sensibly. I suppose that is why MMM has created a mixed research group so that we can help each other instead of bothering him each time.

Hierarchy of role: Knowledge producer and communicator (Jenny)

I was asked to do a nano-coating by my supervisor DDDD a few months ago…DDDD was contacted by the company for it. He forwarded that email to me…I spent some time [researching] on it and told DDDD that it would not be possible by proposed MMMM method. But then, I later came to know that the company was told that the work has been done already…I understood this conversation eventually when DDDD had to send me a thread of emails while he was away for a conference. Reading that, and I was like 'I can't believe he has actually said that to the company!' He knew that I haven't even started working on the coating at that time. I got to know later on that it was hard to achieve those coatings by MMMM method but DDD had mentioned them that work was processing well. If I should have been involved at the initial stage itself, I would have cleared it. It created some tension then. But, at this stage, when I have other tensions and frustrations of writing up my thesis, it does not bother me much. But it used to when I was working in the lab. It is not the case that I don't get to speak to with company people at all, but, I am not involved in all of the conversations. Sometimes, if it is small company start-up company with a limited budget that should be used carefully. There is a big trust build in the process on us, the researchers. So, we, the researchers, should know all about the requirement and conditions transparently….and then only we can help in a better way. If there is not enough information going back and forth between the companies and the researchers who are actually working for them, it becomes 'a leak' in the system; at least I would address it as.

Appendix 3 List of crafted stories

No.	Name of researcher	Titles of the crafted stories
1	Alan	Skill of simplification Building learning ‘bottom to top’ Adopting common vocabulary Disciplinary knowledge as building blocks Being there when needed
2	Anna	Not all instruments are central Constructing results and perspectives of disciplines Micro-planning of experiments
3	Ronan	AFM Understanding ethics in biology Sharing research laboratory
4	Alana	Identifying self Initiating new research objectives Hands on experiments
5	Ciaran	Sharing and questioning information Judging work from lenses of other disciplines Nanoscale at nexus of physics and chemistry
6	Ruth	Multiple disciplines at the instruments (Ruth) Smart materials at nanoscale Knowledge world of chemist
7	Michael	Sharing knowledge world Sense of responsibility Channel of communicating new knowledge
8	Sean	Transparency about publishing research Problem solving in group

9	Susan	Organising research and micro-planning Complementing research of colleagues Learning by teaching
10	Gordon	Exploring magic world of nanoscience Creating appropriate environments in laboratory
11	Eva	Going back to the disciplines Networking with ‘non-specialist’ Graphing research data
12	Adam	Dealing with the expectations
13	Aoife	Learning method by yourself
14	Amanda	Politics of research
15	Mark	Taking initiative and expanding research interest
16	Olan	Communicating ‘what’ matters! Bridging the gap
17	Mick	Sharing equal responsibility Trust but ask question!
18	Brian	Conflicting interests
19	Ross	It is not engineering
20	Damian	Working together Discussing ideas at informal stage
21	Jenny	Hierarchy of role: knowledge producer and communicator
22	Maria	Connecting to the basics (principles of technique) Simplification is strength of coordination
23	Thomas	Language of other disciplines Keep short at broad platform

24	Paddy	Blood plasma and ionic plasma Creole of language Commercialising research
25	Colm	Politics of conference Collaboration- ticket for job Multidisciplinarity of nanoscience

(Note: The crafted stories mentioned in Appendix 3 can be made available on request)

Appendix 4 Quantitative survey

The quantitative survey included two questions (tick box type) given below.

Q.1) Please rank the following attributes (knowledge, skills and competences) required for nanoscience research on the scale of 0 to 5. (0: least necessary, 5: most necessary)

1. Communicating findings to a broader audience (within & outside the discipline)
2. Initiating research activities
3. Explaining the strengths and limitations of the discipline effectively
4. Critical thinking
5. Project management
6. Teaching undergraduate project students from different disciplines
7. Working with researchers from other disciplines
8. Understanding broader goals of the collaborative research
9. Simplifying explanation of the methodological steps with flow charts, diagrams or other methods for colleagues.
10. Acknowledging contribution of other disciplines in your own research
11. Trusting the knowledge from other disciplines
12. Keeping transparency about the authorship credit in a collaborative research
13. Demonstrating the understanding of ethical issues

14. Encouraging an environment for informal discussion in laboratories

15. Sharing research experiences with colleagues

Q.2) Nanoscience spans over a range of core disciplines. Based on your experience please select the appropriate explanation(s) about the disciplinarity of nanoscience. (You may select more than one.)

1. **Separate discipline:** Merging all the scientific and engineering disciplines such that researchers are expected to know everything about the involved disciplines.

2. **Multidisciplinary area:** Researchers work in their core disciplines and the new knowledge is developed at the boundary of the involved disciplines.

3. **Interdisciplinary area:** Researchers have knowledge of different disciplinary perspectives simultaneously and develop a newer body of knowledge from it that is common to all the disciplines.

4. **Boundary spanning area:** The researchers work in their core discipline. In addition, they explore the ways/possibilities of crossing the boundaries of the disciplines to develop new context (research) specific knowledge.

The responses collected from Q1 are presented in the form of a bar chart as shown in Figure 1.

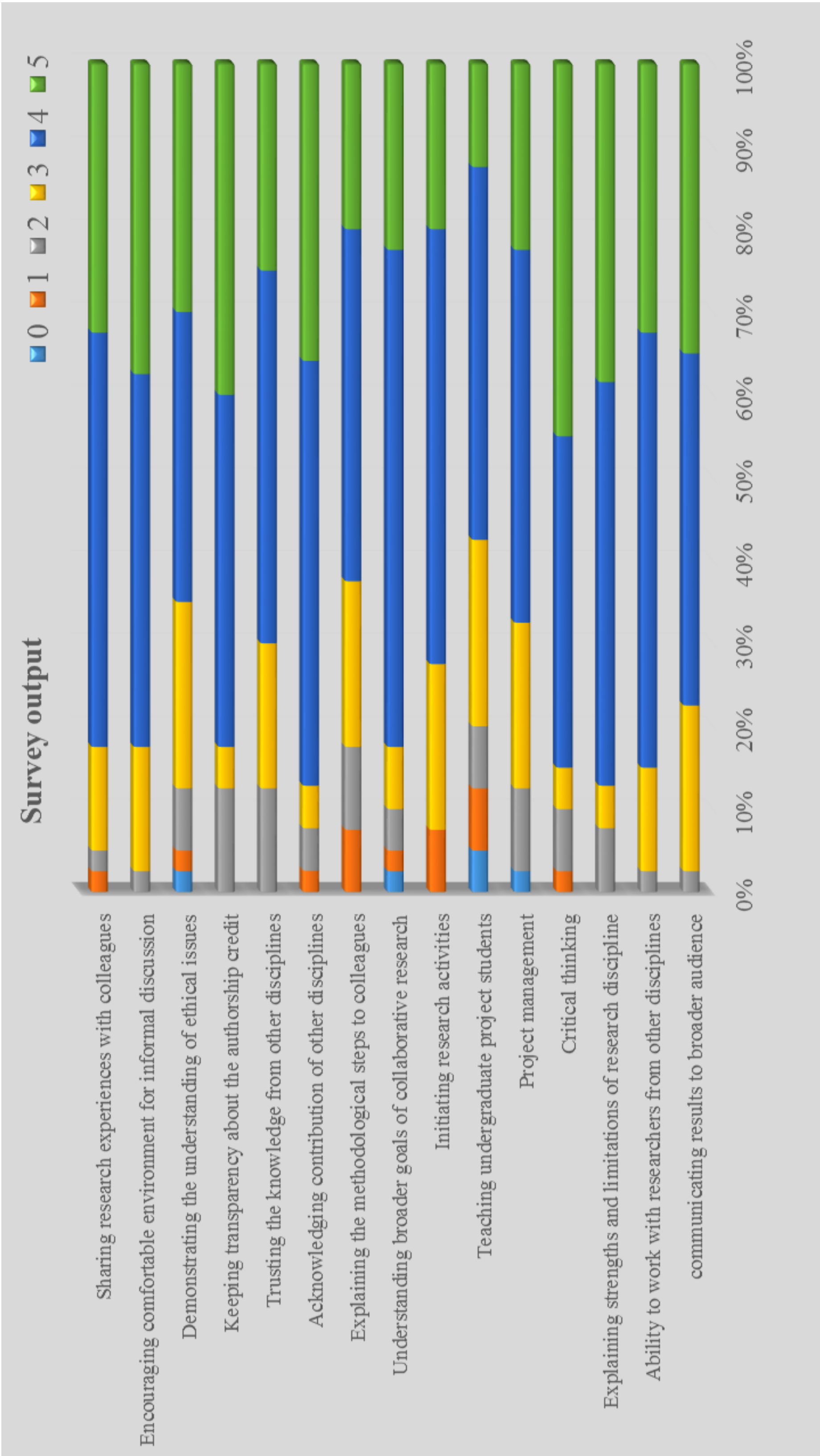

Figure 1 Ranking of attributes (knowledge, skills and competences) for nanoscience research on 0-5 scale

The responses collected for Q2 are shown in the pie chart (Figure 2) below.

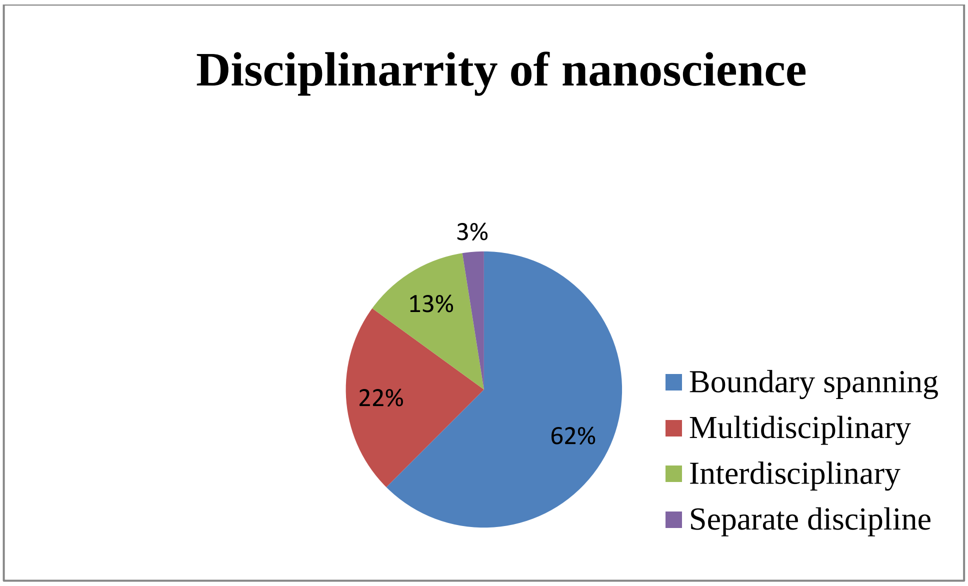

Figure 2 Disciplinarity of nanoscience area

Out of the total 52 responses collected from the quantitative survey, 62% researchers agreed with the description of nanoscience as a 'boundary spanning' area. The 22% of researchers selected multidisciplinary and 13% selected the interdisciplinary alternative while a very small percentage (3%) considered nanoscience as a separate discipline. The majority of the researchers agreed the boundary spanning characteristics of nanoscience research and thus supported the findings of hermeneutic interpretive phenomenological study. As discussed in section 6.2.1, superficial boundary spanning indicated a multidisciplinary character of nanoscience, which can be explained by the 22% results in the favour of multidisciplinarity. Further, as commented in chapter 6, nanoscience shows characteristics of both multidisciplinarity and interdisciplinarity which explains the results for multidisciplinarity and interdisciplinarity. The smaller margin between these (multidisciplinarity and interdisciplinarity) two also indicates that promoting any one particular perspective is not recommended for curriculum development in this area.

The researchers ranked the following skills (and competences) as most important i) acknowledging the contribution of other disciplines ii) sharing research experience with colleagues iii) understanding broader goals of collaborative research iv) Explaining strengths and limitations of their discipline to researchers from other disciplines and v) critical thinking skills. In summary, the quantitative survey outcomes are in good agreement with the findings of this hermeneutic interpretive phenomenological study.

Appendix 5 List of publications

Peer reviewed journal papers

1. **Deepa Chari**, Paul Irving, Robert Howard and Brian Bowe 'Identifying knowledge, skill and competence for nanoscience and nanotechnology research: study of researchers' experiences', Special issue on current trends in nanotechnology education, International Journal of Engineering Education Vol. 28(5), pp 1046-1055, 2012.
2. **Deepa Chari**, Robert Howard and Brian Bowe 'Disciplinary identity of nanoscience and nanotechnology research- A study of postgraduate researchers' experiences', International Journal for Digital Society, Vol. 3(1), pp 619-616, 2012.

Conference proceedings

1. Deepa Chari, Paul Irving, Robert Howard and Brian Bowe 'Phenomenological study of researches experiences of nanoscience and nanotechnology research' International Conference on Education, Research and Innovation, 14-16 Nov 2011, Madrid, Spain
2. Deepa Chari, Robert Howard and Brian Bowe 'Identifying the knowledge, skills & competence for Nanoscience and Nanotechnology research' Ireland International Conference on Education, 3-5 Oct 2011, Dublin, Ireland

Oral presentations

1. Deepa Chari, Robert Howard and Brian Bowe 'Hermeneutic phenomenological analysis of postgraduate researchers' experiences of nanoscience and nanotechnology research' International Research Methods Summer School, 14-16 June 2013, Limerick, Ireland
2. Deepa Chari, Robert Howard and Brian Bowe 'Postgraduate researchers' experiences of nanoscience and nanotechnology research- a

phenomenological study' World Conference on Physics Education, 1-6 July 2012, Istanbul, Turkey.

3. Deepa Chari, Paul Irving, Robert Howard and Brian Bowe 'Phenomenological study of researches experiences of nanoscience and nanotechnology research' International Conference on Education, Research and Innovation, 14-16 Nov 2011, Madrid, Spain.
4. Deepa Chari, Robert Howard and Brian Bowe 'Identifying the knowledge, skills & competence for Nanoscience and Nanotechnology research' Ireland International Conference on Education, 3-5 Oct 2011, Dublin, Ireland.

Poster presentations

1. Deepa Chari, Robert Howard and Brian Bowe 'Hermeneutic phenomenological analysis of researchers' lived experiences of the nanotechnology research. American Association of Physics Teachers, winter meeting, 4-8 Jan, 2014, Orlando, Florida, USA.
2. Deepa Chari, Robert Howard and Brian Bowe 'Postgraduate researchers' experiences of the nanoscience and nanotechnology research- a phenomenological examination', IOP Ireland spring weekend meeting, 22-23 Mar 2013, Galway, Ireland.
3. Deepa Chari, Robert Howard and Brian Bowe 'Understanding the nanoscience and nanotechnology research and associated disciplinarity- a qualitative study' IOP Ireland Spring Weekend Meeting, 21- 22 Mar 2012, Dublin, Ireland.
4. Deepa Chari, Robert Howard and Brian Bowe 'Research design for a qualitative study to identify the knowledge, skills and competences required for the nanotechnology research' 7th Nano-Bio Europe International Congress and Exhibition on nanotechnology, 21-23 June 2011, Cork, Ireland.

5. Deepa Chari, Robert Howard and Brian Bowe ‘Towards the development of an efficient workforce for nanoscience and nanotechnology research’ Nanotechnology: Research Excellence and Commercial Opportunities, 31 Jan – 1 Feb 2011, Carton House, Kildare, Ireland.
6. Deepa Chari, Laura Walsh, Robert Howard and Brian Bowe ‘Study of undergraduate students’ experiences about nanoscience and nanotechnology summer research projects’, Nano-bio postgraduate research symposium, UCD, 14-15 Oct 2010, Dublin, Ireland.