Expertise in Interdisciplinary Science and Education

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Abstract: Many degree programs in science and engineering aim at enabling their students to perform interdisciplinary problem solving. In this paper we present three types of expertise that are involved in different ways in interdisciplinary problem solving. In doing so we shall first characterise two important epistemological challenges commonly faced in interdisciplinary problem solving, namely the communication challenge that arises from the use of different concepts within different scientific domains, and the integration challenge that arises from the differences between domain-specific epistemological standards. Next, drawing on recent work on expertise developed within science studies, we characterize the interactional expertise that is a precondition for scientists to communicate across scientific domains, and the integrational expertise that is a precondition for scientists to be able to integrate cognitive resources originating in different domains. Finally, we shall analyse how different types of interdisciplinary problem solving sets different requirements for interactional and integrational expertise and discuss the implications for science and engineering programs in higher education.

Keywords: interdisciplinarity, expertise, integration, interactional expertise, integrational expertise.

1 Introduction

It is often argued that the complexity of the challenges that face society today – from cancer to climate change – makes them inherently interdisciplinary, requiring an integrated interdisciplinary approach to be solved (e.g. (NAS 2004)). There is therefore a global trend to promote interdisciplinary research and innovation that cuts across the traditional science and engineering disciplines. A striking example is the National Nanotechnology Initiative in the USA which in 2014 alone will spend an estimated $1.5 billion on research and education in nanotechnology[1]. Other examples of interdisciplinary research fields that are receiving increased attention and funding in these years include biotechnology, environmental science and systems biology.

The vision that more of tomorrow's problem solving should be interdisciplinary affects today's higher education. It is here that tomorrow's interdisciplinary practitioners are being trained, often through special interdisciplinary programs that draw on different domains from science and technology[2]. Students in these

[1] http://www.nano.gov/about-nni/what/funding

[2] We speak of 'domains' rather than 'disciplines' to highlight that interdisciplinary problem solving does not necessarily involve different disciplines. For instance, interdisciplinary problem solving regularly occurs between sub-disciplines of

interdisciplinary programs have to divide their time between these multiple domains and therefore cannot be expected to gain the same kind and degree of expertise in all these domains as traditional, monodisciplinary specialists. Although often raised as a concern, this need not necessarily be a problem, as the aims of the two types of educational programs are not identical. The important point is to make it transparent what kind of expertise the students gain from their education and how their specific expertise profile relates to the kind of interdisciplinary problem solving that they are expected to engage in.

Research in higher education on the expertise that students in interdisciplinary programs need to acquire in order to participate in interdisciplinary problem solving and the kind of training needed for students to acquire this expertise has remained limited and to a large extent explorative (fore reviews see (Borrego, Newswander 2010, Spelt et al. 2009)). Further, while the literature on interdisciplinarity is relatively rich in the humanities, social- and health sciences, there has been less tradition for analyses of interdisciplinary processes across different domains within the natural and engineering sciences (Borrego, Newswander 2010). In this paper we therefore focus explicitly on interdisciplinary problem solving in the natural and engineering sciences, the challenges it involves, and the expertise needed to overcome these challenges.

The paper proceeds as follows: First, we shall characterize two general epistemic challenges faced in interdisciplinary problem solving, namely a) how to establish efficient communication across different scientific domains and b) how to integrate cognitive resources from different scientific domains. Next, drawing and elaborating on analyses of expertise developed within science studies, we introduce a distinction between contributory, interactional and integrational expertise that can be used to describe the different kinds of expertise needed for interdisciplinary problem solving. Finally, we shall briefly discuss how science and engineering programs in higher education can train students to obtain these various kinds of expertise.

2 Two epistemic challenges faced in interdisciplinary problem solving

Interdisciplinary problem solving is characterized by aiming for a significant degree of integration of knowledge, methods, models and other cognitive resources from a number of different domains.[3] Here we take an integrated solution to a problem, to be a solution which as a minimum is acceptable relative to the epistemological standards of all domains involved in the problem solving process (see Introduction). We shall here focus on interdisciplinary problem solving that draws on and integrates cognitive resources from a number of different domains within the natural and engineering sciences.

Interdisciplinary problem solving is commonly said to be wide when it integrates resources originating in very different disciplines such as, for example, chemistry and ecology, and narrow when it takes place between sub-disciplines within the same broader discipline (Klein 2010), such as integration of cognitive resources from multiple biological sub-disciplines (Bechtel 1986). Our analysis shall encompass both narrow and wide

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biology (Brigandt 2010). We therefore use the more plastic term 'domain' to refer to both disciplines, sub-disciplines, and other social units of science (Collins 2011).

[3] If it does not aim for a high degree of integration it is commonly referred to as multidisciplinary (Klein 2010).

interdisciplinarity with the aim of clarifying the difference in expertise profiles that is required for narrow and broad interdisciplinarity, respectively.

It is well-documented that interdisciplinary problem solving poses special challenges, exactly because it draws on and integrates cognitive resources from different domains. This has been described in first-hand contemporary accounts from practitioners (e.g. (Öberg 2009, Campbell 2005, Lélé, Norgaard 2005, Jakobsen, Hels & McLaughlin 2004)), in historical and contemporary case studies from science studies (e.g. (Brigandt 2010; Galison 1997; Bechtel 1986)), and in accounts by educators involved in interdisciplinary programs (e.g. (DeZure 2010; Repko 2008; Klein 1990)). Two epistemological challenges figure consistently in all three strands of literature: First, communication across domains can be difficult due to differences in the concepts used in different domains. Second, integration across domains can be difficult due to differences in the epistemological standards of the domains involved. We describe these two epistemological challenges in more detail in sections 2.1. and 2.2. below[4], and analyse the kinds of expertise needed overcome them in section 3.

2.1 Communicating across domains

One of the key challenges to interdisciplinary problem solving that figures prominently in the literature is the communication challenge that arise from the fact that different concepts are used within different domains to describe aspects of the same or overlapping natural phenomena. These conceptual differences between domains can be of different kinds. First, scientists from different domains may develop different concepts to describe a phenomenon. For example, Lélé and Norgaard (2005) have shown that within the domain of soil science, different taxonomies of soil are used when addressing questions related to, for example, fertility or sustainability. Second, scientists from different domains may not use the same concepts in precisely the same ways. There are many examples of this from both research and education settings, such as differences in the meaning of the term 'gene' within research in the biological sciences (Rheinberger, Müller-Wille 2010), or differences in what is meant by 'thermodynamical system' in textbooks from physics, chemistry and mechanical engineering and how that leads to different conceptions of energy conservation (Christiansen, Rump 2008).

In order to communicate across domain boundaries, scientists engaged in interdisciplinary collaborations often need to take recourse to a slightly simplified language. Based on a detailed study of the interdisciplinary collaboration between scientists and engineers at CERN, Galison (1997) described how experimenters, theorists and instrument makers developed a "pidgin language" by reducing mathematical structure, suppressing exceptional cases, simplifying explanatory structure, and minimizing internal links between theoretical structures.

Similarly, Petrie (1976) has argued that a minimum requirement for interdisciplinary work is to learn the observational categories and the meaning of the key concepts of the other discipline (Petrie 1976, p. 37). For

[4] It is beyond the scope of this paper to address *institutional* challenges involving, for instance, difficulties in achieving the resources - financial, physical and temporal - that are required to perform interdisciplinary problems solving or difficulties in achieving recognition for results obtained through interdisciplinary problem solving (Felt et al. 2013; NAS 2004; Campbell 2005; Rhoten, Parker 2004).

higher education this implies that an important aspect of training students for interdisciplinary problem solving is to teach them the key concepts from a number of different domains. This implication is also prominently reflected in the educational literature where it is frequently stressed that the learning outcomes of interdisciplinary programs need to include that students should be able to define key terms from several domains and to develop a common vocabulary with collaborators from other domains (Borrego, Newswander & McNair 2007). At the same time, it is also often stressed that this necessarily results in fewer topics being taught in traditional ways, which potentially limits the students' chances to develop a sufficient cognitive depth to eventually make research contributions in any domain (Davies, Devlin 2007; Golde, Gallagher 1999). We return briefly to these implications in section 3 after we have introduced the other important challenge to interdisciplinary problem solving.

2.2 Doing integration: Negotiating differences in epistemological standards

Interdisciplinary problem solving is characterized by aiming for a significant degree of integration in the final results. Achieving integration requires more than fluent communication. It requires that the participants bridge the differences between the involved domains in the standards used when selecting relevant problems and standards used to evaluate potential solutions to relevant problems (Borrego, Newswander 2010, Spelt et al. 2009, Klein 1990, Repko 2008). We refer to these standards collectively as epistemological standards. Studies of interdisciplinary collaborations in general (Eigenbrode et al. 2007) as well as detailed case studies of, for example, research in the biological sciences (Brigandt 2010) show that, in practice, it is often differences in epistemological standards for what counts as good evidence and a satisfactory explanation that can become either a source of disagreement or a source of mutual enrichment in interdisciplinary problem solving. Studies further show that if the differences in epistemological standards are discussed openly and constructively they can create a fruitful synergy leading to better research (O'Rourke, Crowley 2013). On the other hand, if the differences are not discussed they can cause the problem solving process to stall (Öberg 2009). In the literature on interdisciplinarity in higher education this is reflected in the description of learning outcomes such as the students being able to compare and contrast research values from different domains (Borrego, Newswander & McNair 2007; Lattuca, Voigt & Fath 2004)

Open discussion of epistemological standards requires that scientists participating in interdisciplinary problem solving have a fairly detailed understanding of their own epistemological standards and how they differ from those of their collaborators (Bromme 2000). Knowledge of epistemological standards forms part of what Flavell (1979) called meta-cognitive knowledge. Developing meta-cognitive knowledge in turn requires meta-reflective skills[5]; i.e. skills in critically reflecting on the problem solving practices that a person is most familiar with. Meta-reflective skills include general skills in critical thinking which are valuable for analysing explicit arguments and reasoning patterns, but meta-reflective skills also include skills in identifying and articulating assumptions and standards implicit in specific problem solving practices, for example, specific types of experimentation or computer simulation techniques. To this end it will be important be to have some training in using the most relevant concepts and distinctions developed within science studies for this very purpose.

[5] These skills are *meta*-reflective in the sense that they are used to reflect on the tools that are normally used to reflect on science problems.

Since problem solving practices are to some extent domain specific, the skills relevant for analysing these will also to some extent be domain specific. In some domains it will, for instance, be important to be able to reflect critically on the use of model organisms or randomized controlled trials in a problem solving process using relevant concepts and distinctions developed within science studies. In the case of randomized controlled trials it will, for instance, be relevant to draw on analyses from science studies on causality (Hitchcock 2012) and probability (Hájek 2012). In other domains it will be more relevant to reflect on the use of mathematical models or computer simulations.

Since meta-reflective skills are applied and trained in reflection on personal experience, it is important to have some experience with relevant problem solving practices before engaging in meta-reflection on these; the more and the more varied the experience, the better. Once developed, meta-reflective skills will enable scientists to continuously develop a more nuanced and realistic view of the epistemological standards of the domains they are trained within.

3 Expertise in interdisciplinary problem solving

In science studies, a distinction between *contributory* and *interactional* expertise introduced by Harry Collins and Robert Evans (2007, 2006, 2004) has become widely used for analysing interdisciplinary collaboration and communication among scientists and between scientists and non-scientists (for an overview see chapter 2). In this section we shall argue that this distinction can be adapted to higher education to describe the various kinds of expertise that science and engineering programs should aim to train their students for.[6] At the same time, we shall argue that research from higher education can also enrich the discussion of expertise within science studies and in particular that an additional category that we shall call *integrational* expertise is needed to describe the expertise aimed for in interdisciplinary programs.

In their work on contributory and interactional expertise, Collins and Evans have adopted a skill based view of expertise. Hence, on their account, expertise is not only characterized by the amount of factual knowledge that an individual has accumulated, but also by the tacit knowledge gained by the individual. Expertise is therefore primarily characterized by what the expert can *do* and only secondarily by what the expert must *know* in order to do this. This is in keeping with the development in education towards evaluating student skills as well as factual knowledge (Anderson, et. al. 2001). In this paper, we take expertise to be sets of skills that allow an individual to perform certain tasks that are deemed important by a wider community in a way that benefits that community.

Originally, Collins and Evans introduced the distinction between contributory and interactional expertise in a given domain as the distinction between having "enough expertise to contribute to the science of the field being analysed" and having "enough expertise to interact interestingly with participants" from the field, respectively (Collins, Evans 2002, p. 254). Elaborating on this distinction, we shall characterize *contributory expertise* with respect to a given scientific domain as the ability to make a significant contribution to the

[6] In adapting these notions to an educational setting we do at some points deviate from Collins and Evans' original characterizations. For further discussion see chapter 2.

development of the practice of the domain. By a significant contribution to a domain's development we understand a non-trivial contribution to a study published in a journal or presented at a conference where it is received and assessed by other scientists from the domain. A non-trivial contribution includes as a minimum a contribution to the conception or design the study or the execution of the study, for instance through a non-trivial contribution to the analysis of data, or the interpretation of data, and in addition a non-trivial contribution to the final communication of the results, for example, by writing or critically reviewing significant parts of the manuscript. On this characterization, contributory expertise in a scientific domain requires not only mastery of the domain's concepts, but also skills related to the construction of novel scientific results such as gathering and/or analysing of data, construction and performance of experiments, calculations or simulations. In contrast, for example, performing routine laboratory work following a plan conceived by others is not seen as a significant contribution (although it can, of course, be quite labour intensive)[7]

The paradigmatic example of a contributory expert is therefore the monodisciplinary specialist. As noted earlier, there is some concern that the broad span of interdisciplinary programs prevents students from learning enough to achieve contributory expertise in any domain. Whether contributory expertise in some domain is a necessary condition for engaging in interdisciplinary problem solving is a question beyond the scope of this paper. Our main concern is the question of what kind of expertise scientists need in order to, first, communicate with other scientists who do have contributory expertise in the domain, second, participate in the integration of cognitive resources from these domains and the domains which the scientist is most familiar with. We argue that overcoming these specific challenges requires a kind of expertise that goes beyond contributory expertise in any one domain, and that contributory expertise in some domain is therefore not sufficient for engaging in interdisciplinary problem solving.

As described above, to communicate across domains scientists need to be able to understand and use the key concepts of the domains they are communicating about. This implies that the collaborators should be able to express claims from their own domain in a simplified form understandable to their collaborators and also to understand such simplified claims formulated by their collaborators from other domains. However, for the purpose of communication it is not essential that they can actually contribute to the ongoing research in these other domains, and skills in performing advanced experiments, detailed mathematical manipulations are therefore not necessary. We characterize *interactional expertise* in a domain as some degree of familiarity with the concepts used in a domain while not necessarily having the further skills needed to perform experiments and detailed mathematical manipulations. This characterization of interactional expertise captures the requirement often described in interdisciplinary programs that students need to achieve "adequacy" in

[7] Our characterization is similar to distinctions used in some science journals on when a contribution is sufficient for authorship as expressed, for example, in the Vancouver guidelines. The Vancouver guidelines states that "Authorship credit should be based only substantial contributions to (a) conception and design or analysis and interpretation of data (b) drafting the article or revising it critically for important intellectual content; and on (c) final approval of the version to be published" (ICMJE 1988). All the requirements must be met by all authors to a paper published in journals who adhere to these guidelines. Note that our definition implies that it is possible to find papers with the names of persons without contributory expertise on the by-line. Many science journals have not (yet) adopted such restricted requirements for authorship mention, and some of those who have do not enforce them very thoroughly.

multiple disciplines without necessarily mastering them fully (see (Borrego, Newswander 2008) for a review as well as (Boix Mansilla, Duraisingh 2007, Repko 2008, Borrego, Newswander & McNair 2007).

A rich literature exists within science studies on the usefulness of the distinction between interactional and contributory expertise for the understanding of communication and collaboration among scientists and between scientists and non-scientists. For example, it has been argued that the expertise possessed by sociologists of science (Collins, Evans 2007, pp. 31), journalists (Reich 2012) and specialized interpreters (Ribeiro 2007), whose main task is to communicate about or analyse the scientific practices they are in contact with, but not themselves contributors to, can best be described as some degree of interactional expertise. Similarly, Collins and Evans have argued that interactional expertise is important for communication and collaboration among scientists, and that interdisciplinary problem solving would be impossible without interactional expertise (Collins, Evans 2007, p. 32).

However, although in all these cases a necessary requirement for the activity is to be able to understand and use key concepts from the domain in question, there are important differences between the further skills needed for a) collaborating with other scientific domains with the aim of creating new integrated results acceptable to contributory experts from the involved domains, b) analysing existing scientific results with the aim of creating new results within a separate domain such as sociology or philosophy of science that are not integrated with the results analysed, and c) communicating existing scientific results to an audience that is not (or not yet) contributory experts such as it happens in science communication and science education. We shall here not go into the two latter kinds of activities, but focus solely on the integration of cognitive resources from different scientific domains with the aim of creating new scientific results acceptable to contributory experts from the involved domains.

As described above, overcoming the integration challenge requires that the scientists performing the integration have a realistic and fairly elaborate notion of what their own epistemological standards are, and how they differ from those of their collaborators. Gaining this kind of meta-cognitive knowledge in turn requires relevant meta-reflective skills. To engage in interdisciplinary problem solving drawing on a set of different domains, scientists therefore need a combination of interactional expertise in the relevant domains and relevant meta-reflective skills. We call this combination *integrational expertise* in the set of domains involved in the interdisciplinary problem solving process. Characterized in this way integrational expertise is the kind of expertise needed to overcome both the challenge of efficient communication and the challenge of integration described above. An important teaching goal for interdisciplinary programs should therefore be that their students gain integrational expertise.

In the following we shall examine integrational expertise in more detail and analyse how different forms of integrational expertise are relevant to different kinds of interdisciplinary problem solving. In section 5 we shall briefly discuss how programs in higher education can train students to achieve integrational expertise.

4 The fine-structure of integration in science

We start our analysis of the fine-structure of integrational expertise by examining different degrees of interactional expertise, from the very basic to the very advanced. In the one end of the spectrum, basic interactional expertise involves only familiarity with the most basic concepts of the domain in question. Often, scientists will have obtained such basic interactional expertise in a number of domains through the various introductory courses or similar activities early in their education. This basic interactional expertise may suffice for a scientist to establish the communication required for an interdisciplinary collaboration with scientists from another domain (Gorman, Groves & Shrager 2004; Petrie 1976). However, basic interactional expertise alone will not enable the scientist to engage in any substantial way in the practice of the other domain, he will therefore have to defer substantially to the contributory expertise of his collaborators. In collaborations where some collaborators have only very basic interactional expertise, there will therefore have to be a strong division of labour among the collaborators.

In the other end of the spectrum, advanced interactional expertise involves mastery of a significant part of the concepts as well as some of the practices of the domain. As students specialize and get more and more advanced training in a domain, their interactional expertise will gradually increase. Typically, scientists will in this way have obtained a relatively advanced interactional expertise in a few domains closely related to the domain in which they have contributory expertise. Since this advanced interactional expertise enables them to perform more advanced tasks within the domain in question, labour need not be as strongly divided as for scientists with only basic interactional expertise within each other's domains[8].

The close link between basic interactional expertise and strong division of labour has sometimes led to the view that such collaborations cannot be truly integrative but necessarily remain a multidisciplinary juxtaposition of approaches, and that consequently collaborators do not learn from each other (Borrego, Newswander & McNair 2007). However, as we shall argue below, this view overlooks important integrative aspects of collaborations where labour is divided; aspects that require specific meta-reflective skills that therefore need to be taught.

The opposition between interdisciplinary collaborations characterized by mutual learning and multidisciplinary collaboration characterized by division of labour is too simplified. As described by Rossini & Porter (1979) it is only in one particular framework for interdisciplinary problem solving that scientists from different domains interact until they have all acquired a high degree of interactional expertise in each other's domains and jointly reach a solution. Another framework for interdisciplinary problem solving is a group of negotiating experts who exchange contributions in an iterative process until a solution is found. Andersen & Wagenknecht elaborated on this analysis and argued that for the latter framework where expertise remains distributed and group members therefore need to defer to each other's expertise, the collaborators are to some extent epistemically dependent on each other and will therefore have to have trust in each other (Andersen, Wagenknecht 2013). However, in this process scientists do not trust each other blindly (Wagenknecht 2014). Instead, they calibrate

[8] At least, lack of expertise need not be the primary cause of a strong division of labour, but it may be caused by other factors, such as time constraints or geographical distance.

their trust in each other either directly by scrutinizing the work of their collaborators in detail, or indirectly by scrutinizing only the general argument structures and supplementing by referring to sociological indicators of trustworthiness such as reputation and publication record.[9] However, scientists can only perform a direct calibration of trust in areas where they themselves have contributory or very advanced expertise. Otherwise, they will have to rely solely on indirect calibration of trust. Thus, engaging in interdisciplinary problem solving involving domains in which a scientist has only basic interactional expertise requires that she has strong skills in indirect calibration of trust. An important part of the skills needed to perform indirect calibration of trust are the general skills in critical thinking that we described above as one important component of the meta-reflective skills that students need to acquire in order to engage in interdisciplinary problem solving. Hence, the close link between basic interactional expertise and division of labour has implications for which meta-reflective skills are most important for scientists engaged in interdisciplinary problem solving. If scientists have only a basic interactional expertise there will often be need for the general critical thinking skills that is used when calibrating trust indirectly. On the one hand, a high degree of interactional expertise means better possibilities for developing the aspect of meta-reflective skills that is domain specific and which is used when integrating resources from different domains. There is thus a difference in the kind of integrational expertise needed in different types of interdisciplinary problem solving, but also a difference in how strong domain specific meta-reflective skills can be developed depending on the degree of interactional expertise that a person has in a given domain.

Rather than looking at the different degrees of interactional expertise and seeing which meta-reflective skills they call for, we can describe different types of interdisciplinary problem solving that interdisciplinary programs can aim to prepare their students for and analyse which forms of integrational expertise that they each call for. Consider first, interdisciplinary problem solving that integrates cognitive resources from many different domains. This requires some degree of interactional expertise in all domains covered. But in programs covering many domains it will not be practically possible to train students to develop advanced interactional expertise all of them. It is often overlooked that this means that meta-reflective skills, especially the strong critical thinking skills required for indirect calibration of trust in other experts, become very important in cases where scientists have only basic interactional expertise.

Consider next, interdisciplinary problem solving that integrates cognitive resources from domains with very different epistemological standards. Spelt et al. (2009) observed that such programs are likely to experience more difficulties than more narrowly defined programs. Recognizing and bridging substantial differences in epistemological standards involves patient and detailed discussions and challenges scientists to explicate, defend and negotiate their own epistemological standards. Wide interdisciplinary problem solving therefore requires strong meta-reflective skills, both the domain independent skills in critical thinking, but also the more domain specific skills in explicating tacit assumptions and values in the problem solving practices of a given domain. In contrast, narrow interdisciplinary problem solving in which the cognitive resources to be integrated have their origin in closely related domains does not require meta-reflective skills to the same degree.

[9] For analyses of direct and indirect calibration of trust, see e.g. (Kitcher 2002) and (Goldman 2001).

Interdisciplinary programs that span domains with very different epistemological standards therefore especially need to train students to obtain meta-reflective skills.

Finally, it is often argued that interdisciplinary programs are needed in order to educate students to help solve the grand challenges that face us today. This means that the student, using the problem as a starting point, should be able to identify the domains that can contribute to the solution to the problem, and perhaps even identify the relevant experts to draw on. To be able to identify domains that can contribute to the solution to a given problem, the student will need to have at least basic interactional expertise in a number of different domains. However, if, due to time constraints, basic interactional expertise is all that can reasonably be attained within these domains then the student will also need strong skills in indirect calibration of trust in order to identify the right experts within these domains that should contribute to the solution of a given problem. To this end, strong meta-reflective skills, especially the more general critical thinking skills, will be important.

In summary, different kinds of interdisciplinary problem solving call for different forms of integrational expertise. If many domains are involved in an interdisciplinary problem solving process it will be important to have strong skills in indirect calibration of trust. If wide interdisciplinary problem solving is attempted, it will be important to have strong meta-reflective skills, including the domain specific meta-reflective skills used to explicate tacit assumptions and values. Finally, if interdisciplinary problem solving takes a societal challenge as its starting point, it will be important to have at least basic interactional expertise in a number of domains combined with strong skills in indirect calibration of trust.

5 Teaching integrational expertise

Klein argues that many alleged interdisciplinary curricula are actually “multidisciplinary assemblage[s] of disciplinary courses” (Klein 2010, p. 17). On our analysis, the problem with such programs is that while they can provide the interactional expertise required for communication across domains, they fail to provide sufficient meta-reflective skills necessary for integration between domains.

The Kuhnian framework often drawn upon when discussing the challenges of interdisciplinary does offer an explanation of this ((Kuhn 1977, 1996 pp. 187) see also (Andersen 2000)). Kuhn described how in traditional higher education in science epistemological standards from a given domain are taught through exemplars that display the standards to the student. These are then internalized through exercises where students solve problems similar to the exemplar problems. However, while this traditional approach may be efficient in getting the students to accept the epistemological standards of a given domain, it does not necessarily encourage the student to explicate and reflect on them to the extent required when bringing the epistemological standards from different domains to bear on an integrated solution to an interdisciplinary problem. Kuhn’s analysis is on this point vindicated by research in science education showing that simply learning the key concepts of a number of scientific domains does not ensure the development of relevant meta-reflective skills (Klein 1990, Christiansen; Rump 2008; Spelt et al. 2009, DeZure 2010; Borrego, Newswander 2010). Similarly, literature on Nature of Science (NoS) in science education often emphasize that science education focused on cognitive content alone does not automatically give students the kind of meta-cognitive knowledge *about* science that is required for interdisciplinary problem solving, such as knowledge about differences in epistemological standards. This literature therefore highlights the need to give the students opportunities for explicit guided reflection (Abd-El-Khalick 2013).

In developing new initiatives to train meta-reflective skills, important insights can be drawn from both the NoS literature as well as novel initiatives to aid practicing scientists develop meta-reflective skills. Based on her experience from working in environmental science, Öberg (2009) recommends that interdisciplinary research groups explicitly discuss simple questions about the quality of the research produced in the collaboration. A similar approach has been developed by Eigenbrode and collaborators in the so-called "Toolbox Project" (Eigenbrode et al. 2007) that runs workshops for interdisciplinary collaborations in which tailored questions about various philosophical aspects of research are discussed in order to engage scientists in reflection and refine their meta-cognitive knowledge. Similar to Öberg's experience, scientists who have participated in these workshops generally find them relevant and helpful in relation to their interdisciplinary work (O'Rourke, Crowley 2013, p. 1946). The questions covered in the seminars described by Öberg and the Toolbox Project are philosophical in nature and aim to address the differences in epistemological standards present in the collaboration. A number of useful conceptual tools for handling such questions have been developed by philosophy, history and sociology of science[10]. Teaching simple versions of these tools to students can have a significant effect on the students' ability to engage with these difficult questions about the nature of research and innovation (as illustrated in (Scharmann et al. 2005)). Hence, what we suggest is that meta-reflective skills can be developed in interdisciplinary programs by introducing opportunities for explicit reflection, either as part of core science courses, or in the form of specific courses devoted explicitly to reflection and meta-cognition.

6 Conclusion

The challenge facing educators in higher interdisciplinary education is to train the future contributors to interdisciplinary problem solving. We characterized two prominent challenges faced in interdisciplinary problem solving: establishing efficient communication across domains, and the challenge to identify and bridge differences in the epistemological standards of the domains represented in the collaboration.

Interactional expertise has been described as important in interdisciplinary problem solving. We showed that it is indeed relevant for overcoming the challenge to establish efficient communication, but insufficient for integrating cognitive resources from different domains. To this end meta-reflective skills are also needed. We therefore characterized integrational expertise as the combination of relevant interactional expertise and meta-reflective skills and argued that this is the kind of expertise that interdisciplinary programs should train students to gain. We further argued that different interdisciplinary programs should emphasize different forms

[10] It is beyond the scope of this paper to review this literature. For general reviews of history and philosophy of science relevant to education, see (e.g. (Duschl 2008; Matthews 1994)).

of integrational expertise depending on the kind of interdisciplinary problem solving they want their graduates to be able to engage in.

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