Interdisciplinary Projects as an Expert-Network: Analysing Team Work Across Biological and Physical Sciences

Neil Stephens

Social and Political Sciences, Brunel University London, United Kingdom/ Neil.Stephens@Brunel.ac.uk

Phil Stephens

School of Dentistry, Cardiff University, United Kingdom

Abstract

We report an analysis of how an interdisciplinary project bringing together biologists, physicists and engineers worked in practice. The authorship team are the Principle Investigator who led the project, and a social scientist who studied the project as it was conducted by interviewing participants and observing practice. We argue it is accurate and productive to think of the interdisciplinary team as an Expert-Network, which means it was a managed set of relationships between disciplinary groups punctuated by specific junctions at which interdisciplinary exchange of materials, knowledge, and in limited cases, practices, occurred. We stress the role of trust in knowledge exchange, and document how hard sharing knowledge – and especially tacit knowledge - between disciplines can be. Key is the flexible management of the network, as the membership and required skill set change. Our analysis is embedded within, and contributes to, the Sociology of Experience and Expertise (SEE) framework. We close by suggesting advice for others seeking to manage a similar interdisciplinary Expert-Network.

Keywords: Interdisciplinarity, Interdisciplinary, Expert-Network, Biology, Physical sciences

Interdisciplinary work is an increasingly visible feature of science. This given, what it actually means has long remained ambiguous or contested both among those who engage in practices under its name, and scholars who analyse its use in practice (Dogan and Pahre, 1990; Jacobs, 2014; Klein, 2009; Callard and Fitzgerald, 2015; Madsen, 2018). In this paper we discuss and analyse practical issues in delivering projects constructed as interdisciplinary, through a case-study analysis of a particular consortium addressing issues of accurately tracking cell lineages, employing experts from a set of physical and life sciences. This paper is, itself, interdisciplinary, being co-authored by the cell biologist who was Principle Investigator on the grant, and a sociologist who collected data and analysed the progress of the project. As part of this sociological work, a set of interviews and observations were conducted with consortium members across the four-year lifespan of the project to understand the opportunities, challenges and broader experiences of working together. This work is reported here.

Empirical context: The consortium

This consortium was assembled following a funding call from the UK Engineering and Physical Sciences Research Council (EPSRC) to stimulate new research into the area of Novel Technologies for Stem Cell Science. The call was explicitly designed to support interdisciplinary work, mentioning both cross-disciplinary and multidisciplinary approaches in the proposal information. The consortium members themselves were drawn together through an existing infrastructure within the lead institution that had also been developed to support interdisciplinary engagements.

In conducting the project, the consortium's main aim was to develop a set of technologies to help cell biologists track cells and their differentiation state inside the body without opening the body up. The underlying principle of the application was the hypothesis that such research would profit from an interdisciplinary approach, drawing together areas of complementary expertise across the life and physical sciences. The team assembled was cross-School and cross-University, with most members in City 1 and those specialising in rheology in City 2, a similar sized city 55km away.

The project was concerned with developing solutions to overcome a major barrier impeding the translation of stem cell science: the inability to accurately follow cell lineages (the pathways along which stem cells move to become the end-stage cells of our bodies) and also to track them deep inside tissues in a non-destructive way. Specifically, the aim was to develop novel ways of non-destructively labelling stem cells by manipulating molecules within the cells so the consortium can follow both their position and their eventual fate. In order to image the cells, the consortium aimed to develop new microscopic techniques that allow researchers to view these cells in a non-invasive, non-harmful way (unlike prior approaches) and therefore utilise technologies that will eventually enable imaging of these cells deep within patient tissues. Being able to follow these stem cells would also allow the consortium to examine the mechanical influence of surrounding tissue environments. Armed with such knowledge the consortium could then mechanically manipulate the surrounding environment to direct stem cells into a tissue of choice in order to deliver custom designed tissues on demand.

The cell biologists produced two types of cells for the other consortium members to use in developing their novel technologies: neurons and adipose (fat) cells. The cell tracking techniques being developed were the microbiology-led approach of Chemical Exchange Saturation Transfer (CEST) and the chemistry-led approach of non-natural amino acids. The planned visualisation techniques were the physics-led Coherent Anti-Stokes Raman Shift (CARS) and Magnetic Resonance Imaging (MRI). The consortium also included the engineer-led rheological work that would measure the stress and strain readings of cells in a machine called a rheometer. The eventual aim of all of these processes was to provide cell biologists with better tools for observing and controlling cells inside the body.

The project was structured around three work packages across which five 'Post-Doctoral Research Assistants' (PDRAs; 3x biologists, 1x physicist, 1x engineer) worked in collaboration. Work package 1 collated the work on non-destructive stem cell imaging, including both the CARS and MRI/CEST research. Work package 2 contained the rheological work on the microstructural studies of cell differentiation. Work package 3 aimed to extend the rheological work to 3D tissues. Across the consortium project meetings were held every three months to discuss progress and consider next steps according to a project delivery schedule and defined milestones.

In what follows we analyse the work of this consortium over a four-year period through our novel concept the expert-network. First, we review a subset of the existing literature on interdisciplinarity so we can subsequently show how the expert-network concept contributes.

Interdisciplinarity

A large and diverse literature exists considering interdisciplinarity. This includes work from Science and Technology Studies (Nowotny et al., 2001), cognitive science (Bruun and Sierla, 2008), science policy (NAS 2005), scientometrics (Tomov and Mutafov, 1996), philosophy of science (Andersen and Wagenknecht, 2013), the history of science (Graff, 2016), as well as practitioner accounts (Newell et al., 2008). One strand of this work seeks to develop a definition of what counts as interdisciplinarity. Porter et al. (2004), for instance, argue interdisciplinary work involves research by teams that integrate perspectives and concepts, and/or tools and techniques, and/or information and data from two or more sites of knowledge or practice. Parts of the literature set interdisicpinarity alongside similar categories of practice. In this vein, Fiore (2008) reviews interdisciplinary policy literature to identify three existing categories: 'cross-disciplinary' (different disciplines without qualifying the type of interaction), 'multidisciplinary' (coordination of efforts for a common goal), 'interdisciplinary' (systematic integration of ideas) work. Similarly, Nersessian and Newstetter (2014) discuss engineering examples of a multidiscipline, interdiscipline, and transdiscipline (work that transcends discipline through synthesis). While these authors seek generalizable definitions of interdisciplinarity, others suggest that what counts as interdisciplinarity can vary depending upon the disciplinary context of each case (Riesch et al., 2018). Others again choose not to seek closely delineated definitions, instead simply using the term interdisciplinarity to capture all work between people with different expertises (Barry et al., 2008; Jacobs and Frickel 2009). A full review is beyond the scope of this paper, but we direct readers towards Huutoniemi et al. (2010), Klein (1990) or Frickel, Albert, and Prainsack (2016) as valuable resources.

An important theme in the literature is the observation that interdisciplinarity can take different forms. Bruun and Sierla (2008) identify three knowledge networking strategies – modular, integral and translational. *Modular knowledge networking* captures practices in which tasks are divided between autonomously operating agents with a single coordinating site that draws them together. *Integral knowledge networking* describes settings in which a group jointly and holistically addresses a task collectively. *Translational knowledge networking* combines elements of both, as autonomous groups focus upon tasks that have been allotted to them, but then come together to synthesise findings without a central coordinator. Articulating a different typology, Andersen and Wagenknecht (2013) develop the work of Rossini and Porter (1979) with four categories of interdisciplinary work. The first, *integration by leader*, has commonality with Bruun and Sierla's modular knowledge networking, in that a group leader is key to drawing tasks together. The second, *common group learning*, describes a situation in which the research process is characterised by sharing, interlocking intensions and mutual responsiveness which ideally leads to shared mental models and concepts. The third, *negotiation among experts*, involves a shared intention, but less integration with no commitment to genuinely shared final analysis. Andersen and Wagenknecht's (2013) fourth and final category is *joint integration*, which involves continuous integration of intentions and ways of working towards joint results, in a form akin to Nersessian and Newstetter's transdiscipline.

Bruun and Sierla (2008), and Andersen and Wagenknecht (2013), define generic categories of interdisciplinarity. MacLeod and Nagatsu (2018), in contrast, report discipline specific modes of interdisciplinarity. Their study focuses upon environmental sciences to argue that within this discipline interdisciplinary practices have crystallised around four principal integrative methodological platforms that site manageable modes of working across specialisms and allowing interdisciplinary affordances. As discipline distinct cases, these four strategies are all specific to the forms of modelling work undertaken in environmental science. Their relevance here is as an example of cases where interdisciplinarity in practice is limited by practical social issues, a finding also seen in climate science by Duarte (2017).

While some literature articulates the benefits of interdisciplinarity (Nissani, 1997; NAS, 2005), we should also note the minority of texts that explore its problems, weaknesses, and the negative aspects of the political economy of the drive to interdisciplinary work. Jacobs and Frickel (2009) question the soundness of the move towards interdisciplinary research, particularly at the risk to existing and successful disciplinary knowledge, and remain sceptical that interdisciplinary work really does deliver privileged knowledge. Callard and Fitzgerald (2016) explore the role of power asymmetries of real-world interdisciplinary practice, and the emotive effects of these. This theme also features in Albert, Paradis, and Kuper's (2016) study of humanities scholars in medical schools, and Stephens, Khan, and Errington's (2018) analysis of sharing and surveillance among interdisciplinary teams in the life sciences. Barry, Born, and Weszkalnys (2008) embed a recognition of power dynamics within their three-part categorisation of interdisciplinarity, that features the *integrative-synthesis* mode (where multiple disciplines work together), the *agonistic-antagonistic* mode (where intellectual opposition frame exchange) and finally the *subordination-service* mode, where one discipline asserts authority over the other (see Lewis, Bartlett, and Atkinson (2016) for a recent example of the relationship between biology and subordinate bioinformatics). Further engaging with the political economy of interdisciplinarity, both Mody (2016) and Cassidy (2016) detail how institutions use interdisciplinary practice strategically to attract funding (work complemented by Lyall et al.'s (2013) analysis of the role of funding bodies in bringing interdisciplinarity into being). Finally, as Cuevas-Garcia (2018) shows, those conducting interdisciplinary work can also construct those practices as both positive and negative.

Akin to the work presented here, there are examples of studies of interdisciplinary collaboration in the life sciences (Fujimura, 1987; Parker, Vermeulen, and Penders, 2012), with two pertinent examples of stem cell science and tissue engineering consortia (Morrison, 2017; Osbeck and Nersessian, 2010). In the most recent of these, Morrison (2017) reports interviews within a large cross-sector group seeking to produce 1,500 disease-specific induced pluripotency stem cell lines for toxicology testing. Morrison shows his interviewees articulate an ethos of reciprocity set within trust relations across a division of labour. In the context of this large consortium, some collaborative efforts were deemed 'formal', in that their nature and extent were defined in legal documents, while others took on an 'informal' character, which was premised upon different types of trust relationship. Importantly, and similar to the work reported here, Morrison notes the forms of exchange in this setting include the movement of material and data, as well as expertise. This theme is also analysed by Osbeck and Nersessian (2010) in their five-year ethnographic study including a tissue engineering laboratory. Their focus is upon discursive strategies scientists use to position themselves within interdisciplinary groups, related to professional or disciplinary affiliation, knowledge construction, and their relationships to objects and artefacts, particularly the cells themselves. On this last point in particular, Osbeck and Nersessian (2010) argue the scientists' disciplinary identification is related to both their identity as caretakers of the living - and often anthropomorphised - cells, and the relationship of that to the cells' agency as living entities. These scientists' skill, concern, and relationality to the cells as living beings are entwined with disciplinary identities. The themes from both Morrison's (2017) and Osbeck and Nersessian's (2010) work on the role of the material, trust, and identity in interdisciplinary tissue engineering-focused projects will feature in our account of our consortium as an expert-network.

Theoretical perspective: the Expert-Network

The work presented in this paper is informed by Science and Technology Studies, in particular the Sociology of Experience and Expertise (SEE) framework (Collins and Evans, 2002, 2007). We integrate our explanation of this approach into explication of our own novel theoretical contribution, the notion of the 'expert-network'. The SEE perspective was adopted early in the research process of the project described here, and N. Stephens discussed concepts from SEE with consortium members, including P. Stephens, as the project was conducted. Specifically, the notions of tacit knowledge, and contributory and interactional expertise were discussed with consortium members as the project progressed, with a view to developing a reflexive analysis by some consortium members during the work. The sociological component of the project was written into the original research proposal, to support thinking around interdisciplinary practice. This given, the key original theoretical contributions of this paper, discussed below but categorised under the term expert-network, was developed during analysis after the project was completed. In this work we do not seek to define what interdiscipinarity is, or divide it into subcategories, but instead we study how interdisciplinarity is enacted as a practice by those engaged in its pursuit.

Our key argument is that it is productive and accurate to describe the consortium's operation as an expert-network. By this we mean it comprises a managed set of relationships between disciplinary groups punctuated by specific junctions at which interdisciplinary exchange of materials, knowledge, and in limited cases, practices, occurred. We call these junctions 'disciplinary exchange points' to denote where, when, and how interdisciplinary exchange happened. Through these, the expert-network functions as a form of 'collaborative' or 'collective' interdisciplinarity, in which individuals from different disciplines seek to work together on a project, as opposed to a form of 'individual' interdisciplinarity, in which one person themselves seeks to become expert in multiple domains (Calvert, 2010; Lewis and Bartlett, 2013). Identifying key exchanges of the three types – material, knowledge and practice – is an important step in an expert-network analysis. An important insight from this perspective is that interdisciplinary work can function as much to re-establish disciplinary boundaries as to blur or break them (see also Centellas, Smardon and Fifield (2014) for a similar argument in the field of cancer biology). In an expert-network, scientists retain their status as experts within the disciplinary scope of their own area. Across the network, scientists seek to learn more about the work of other experts through an interest driven by a combination of pleasurable curiosity, trust and bond-building through attentiveness, and a utilitarian requirement to understand each other's work to allow the project to progress. Importantly, this utilitarian interest is informed by a concern over 'how much do I need to know about their work to do my work', or, in some cases, 'when do I know enough to know I can stop learning more about their work'.

In the SEE framework, Collins and Evans (2007) make the distinction between 'contributory expertise' – the full capacity to *do* the work of a scientific discipline (conduct and publish research as a contributor) – and 'interactional expertise' – the ability to communicate in some kind of meaningful way on the topic (but not being able to *do* the work directly) (see also Collins and Evans, 2015, and for use of this concept in other work on interdisciplinarity, see Gorman and Spohrer, 2010, Nersessian and Newstetter, 2014, and Andersen and Wagenknecht, 2013). Expert-networks such as those studied here contain scientists who are contributory experts in their own field, and who are, or are working to become, interactional experts in the fields of their consortia members. For example, as part of work package two, the cell biologists and physicists worked together to develop a functional CARS image analysis system for biological systems that produces non-invasive cell imagining. This could not be achieved without the contributory expertise in cell biology and spectroscopy, and a level of interactional expertise between the two. The disciplinary exchange points here related to knowledge and material, as the cell biologists needed to provide the physicists with (i) cells they could image, (ii) the knowledge to accurately write about this in publication, and, importantly, (iii) a clear sense of what was important and useful for a cell biologist to be able to see in the images produced. Whilst these requirements involved attaining a level of interactional expertise, at no point did the cell biologists engage in building or altering the CARS microscope, just as no physicist worked to culture cells. Both remained within the disciplinary boundaries of their contributory expertise and as such worked to reinforce these boundaries even through this expert-network.

This work of doing and engaging in contributory expertise involves learning some 'tacit knowledge' (Collins and Evans, 2007; Collins, 2010a, 2010b) of the practical craft skill of cell culturing. Knowledge that is tacit cannot be easily articulated in words either because it is an embodied skill, or because those who have knowledge do not recognise the importance of a particular part of their practice. Cell culturing craft skill is an example of specialist tacit knowledge – that of any expert in any domain (scientific or not), and is an essential component of both contributory and interactional expertise that, according to the SEE framework, can only be gained through immersion among those active in that domain. In the empirical sections that follow we will show the role and the challenge of tacit knowledge within the expert-network.

Finally, the SEE framework (Collins and Evans, 2007; Collins et al., 2007) has also drawn upon Galison's (1996) analysis of communication between people who do not share a language and specifically his theorisation of the formation of new languages through jargons, pidgins, and creoles, with each being an example of increasingly complex inter-languages that groups, including scientists, use to exchange ideas. As we will show, the interlanguage developed by the consortium is limited, as it is based upon experts accepting more simplistic terms and characterisations of their ideas as opposed to the development of a novel set of terminologies. The relevance of SEE to studying interdisciplinarity has been noted by Gorman (2002) and Goddiksen (2014). By using this set of ideas in a detailed case-study analysis of interdisciplinary work we believe the notion of the expert-network offers a productive mechanism to orientate the SEE framework towards these ends. In the discussions section, we identify key aspects of this approach that subsequent researchers may also choose to follow in their own work.

Methods

The analysis reported here explores empirically the practical experience of interdisciplinarity across the consortium in a detailed case-study approach. Twenty-nine semi-structured interviews were conducted by N. Stephens over a four-year period with team members from across the range of expertise. Interviews lasted between one and three hours and were recorded and transcribed. Interviewees were asked about the challenges and successes of working in an interdisciplinary context. Ethnographic observations were also conducted and recorded in fieldnotes by N. Stephens at the three-monthly project meetings and during laboratory visits over the four-year period. These day-long three-monthly project meetings in particular were key moments for data collection as the team communicated their progress and negotiated challenges in conducting interdisciplinary work (Stephens and Lewis, 2017).

The project was approved by Cardiff University School of Social Sciences research ethics committee. As part of this, ethical assurances were made to participants that they would be given personal anonymity, so the detailed accounts presented here do not identify the individuals involved. Quoted interviews have been edited for clarity and to retain anonymity. All team members were observed and approached for an interview by email, with seventeen people interviewed, eight more than once, and two members not agreeing to be interviewed for undisclosed reasons.

Interviews and observations were analysed through a thematic analysis by N. Stephens. As PI on the consortium project, it would be inappropriate for P. Stephens to see the data, so all data work was conducted exclusively by N. Stephens to protect the other participants' anonymity. Furthermore, P. Stephens is both participant (as both an interviewee and as a subject of observation) and author. As such, he is represented here in quotations, and as a contributing perspective on the analysis. By remaining reflexively aware of this relationship we believe we have retained the essential ethical guarantees to other participants, and provided a rich analysis to inform both social scientists interested in interdisciplinary work, and natural scientists seeking to be better informed about how they can approach their own interdisciplinary work. As part of this process, as noted earlier, P. Stephens, along with some other members of the consortium, discussed elements of the SEE framework with N. Stephens as the project progressed. These discussions informed the theoretical development as N. Stephens could see which elements of SEE resonated with participants' experience, and used this to formulate the notion of an expert-network. In dialogue with N. Stephens, P. Stephens then led on developing the advice for practitioners of interdisciplinarity that closes this paper.

The stem cell consortium as expert-network

In the following sections, we analyse our empirical material to further develop and substantiate our use of the expert-network concept. We will show the value of studying the interplay of material, knowledge and practice at disciplinary exchange points. We consider three related themes in turn: language and understanding, contributory expertise and tacit knowledge, and managing and reconfiguring the expert-network.

Language and understanding in the expert-network

The interactional form of this expert–network is evident in the following interview quotations. A physicist interviewed early in the project describes the difficulty of understanding the technical practices of others, and how the division of labour across the consortium allowed this to be manageable:

> "I'm quite confident on what I'm doing in my technical part… but I'm quite lost in the whole picture of the consortium in terms of what is interesting to measure… all this biology part is really something that I'm quite lost on."
>
> Interviewer: "Do you feel that's a problem?"
>
> "Hmm, I would say it would be better if I could understand it, but probably as *I don't need other people in the consortium to do my job*, probably other people in the consortium *don't need me to do their job*." [Emphasis added]

This clear identification of disciplinary roles and associated actions were key to how consortium members self-identified and located themselves in relation to others. Speaking towards the end of the project, an engineer explained how a level of knowledge exchange had occurred, but also reiterated the previous physicist's focus upon a division of labour across the expert-network:

> It's good to have an interest and appreciation of a lot of these different techniques, especially when you come to reviewing papers etc. But I would never want to become an expert at that kind of thing. *I think you need to focus on what you know already*. [Emphasis added]

Both these accounts, from a physicist early in the project, and an engineer late in the project, demonstrate how individuals in the expert-network use the network itself to assert the boundaries of their own disciplinary identities and practices, in terms of 'doing their job', or focusing upon what they 'already know'. In contrast to the fluid interdisciplinary identities reported in Brew (2008), the experience of collaboration here worked to further embed existing roles as the expert-network defines and delineates their expertise, not blur it into other domains. This given, a number of consortium members did have previous experience of other members' expertise, via previous projects or teaching together on University courses, but they retained a sense of, as one interviewee described, a "fundamental home" discipline.

During the three-monthly project meetings, a local and situated interlanguage arose as experts in different disciplines formed a basic shared vocabulary to explain their thinking to each other (Stephens and Lewis, 2017). Key to doing this successfully was knowing both what needed to be known by others and what did not need to be known by others. In a clear example of this, the presentations by the physicists at the three-monthly meetings in the early part of the project provided detailed accounts of the mathematics of spectroscopy and the computer algorithms used by the CARS system. Over time the presenting physicist chose to include less of this detail because, as interviews revealed, the physicist felt the broader consortium did not need or want to grapple with this discipline specific technical information (see also Stephens et al., 2018). By this stage, across the group, a shared understanding had arisen as to how much consortia members needed to know of the physics, and, equally importantly, that the group trusted the expertise of the physicists to continue appropriately. The physicists were themselves learning how much they needed to know of the expertise of others, and making judgements as to why, as articulated by another physicist in an interview half way through the project:

> Of course, it is frustrating if you don't fully understand, so where is the balance between how much I really need to understand that aspects of biology in detail, how much I can rely on what someone tells me, how much someone needs to know about how I do CARS microscropy. Someone doesn't have to know all the details but it's enough if they understand which kind of images we can generate and I think this process is very much also

> depending on people. So… having them explain enough so that *I have enough of an understanding but also knowing that, okay, at some point I don't need to know all these details*, but I have enough understanding to say, "I think this is something we can do together. This is an interesting problem; let's go in this direction". [Emphasis added]

Here judgements are being made as to what constitutes 'enough' knowledge for an individual to have about others, and what others need to know about them. Ascribing 'enough-ness' is linked to practical issues of establishing shared visions and expectations to allow each to do what they need to do and achieve what they need to achieve within the limits of their disciplinary interest. When communicating outwards across disciplinary boundaries, the focus is on simplicity to facilitate progress. A similar account was provided by an engineer below, that, like the example above, shows the inter-language of the consortium was premised upon contributory experts accepting a loss of accuracy and nuance in the terms used by others to explain their work:

> That has been a challenge, converting the general kind of language into correct rheological language. But I'm used to that, I work with clinicians (laugh), people call things sticky just because it's thicker, more viscous. Viscoelasticity isn't stickiness at all *but you kind of forgive them because you know what they are on about*. [Emphasis added]

Forgiveness here recognises the inherent limitations and challenges of disciplinary ties, an appreciation of the need for a shared resolution to the situation, and a willingness to forego the level of accuracy normal within their own discipline in order to pursue practical solutions. This given, while the knowledge-focused disciplinary exchange points were typified by simplified understandings, there were still levels of differentiation within the consortium, as interviewees often articulated which expertise domains they needed to understand better, based upon those disciplinary exchange points within the project, as evident in this cell biologist's account:

> I probably need to understand what [the chemist] is doing more than I need to understand the rheology or the CARS. The rheology and the CARS is more technical, the constructs that [the chemist] is going to provide are actually going into the cells so I do have to understand that bit.

Equally, respondents had a view on which other expertises they were best placed to understand, based upon a sense of which disciplines are closer to their own disciplinary identity and contributory expertise, as articulated by an engineer:

> Being an engineer, I like to understand the physics to a certain extent. Biology is a different language again.

The three-monthly meetings continued to be sites for disciplinary exchange points on the knowledge of each other's practice, although the inter-language that arose was limited to the core ideas that each expert felt they needed to know to progress their own work. Describing this in terms of the interactional experience of being at the meetings, one scientist recalled:

> I think sometimes in our consortium meetings, people easily end up - because it's natural - talking with their own language and other people don't always want to really stop them and say, "well, I don't really understand a word. Can you really explain everything again in a completely different way," because partly you maybe don't want to be rude, partly you maybe think, '*well, I don't have to know all those details*,' partly you don't want to demonstrate that you still haven't understood these things. So there are all these combinations where out of laziness mixed with maybe being a bit shy, mixed with maybe thinking, '*well, you know, I don't have to know all of that*.' I think in these meetings, especially with time, people are less and less prone to ask questions. [Emphasis added]

Attaining a workable model of what counted as enough knowledge and understanding of other expertises was essential to the group's progress, as this utilitarian approach to interactional expertise was used across the expert-network, premised upon a simplified inter-language. In the next section, we explore the limited case in which the disciplinary exchange point required the translation of practices in a limited form of contributory expertise.

Contributory expertise and tacit knowledge in the expert-network

Inherent to our notion of the expert-network and the SEE perspective is the recognition that scientific work and contributory expertise is premised upon specialist tacit knowledge. This was described by one cell biologist - the project PI and second author on this paper - in an interview during the early stages of the project, in terms of an often used gardening analogy: "it's the nuances, it's having green fingers and knowing how to do certain things in certain ways, especially with tissue culture, is really important". Another team member, a chemist showing their awareness of the craft skills needed, described stem cells as "very finicky things", to capture their fussiness, and that they are difficult to please. This framing captures the craft skill of cell culturing, and the specific, sometimes idiosyncratic, behaviours attributed to in vitro manipulation (Stephens et al., 2011; Osbeck and Nersessian, 2010; Meskus, 2018). Cell biologists frequently assess the state of cells by describing them as 'happy', as evident in this account: "I think with the cells you get used to the way they look, and shape and size of the cells change depend on whether they're happy or not happy. So that's just general morphological features." Later, the same cell biologist explained the relevance of this for the expert-network, in the context of the differing needs and existing knowledges of the team members, to show how experts across the group were able to gain enough understanding of what 'happy' meant, and how it was achieved:

> One of the issues is that we're trying to adapt the [CARS] instrumentation so that we can do life cell imaging. Which means the cells have to be kept happy, which is temperature and gas. But because the MRI group… are aware of the modification of the environment [through their previous projects]. It's just the same skills. But I did take [a physicist] up to our laboratory to show him the incubators that we use to incubate the cells to keep them happy. I showed him the cells down the microscope... So they have seen my lab I've seen their lab which is good.

Equally, an engineer drew upon a different analogy from popular culture to capture the tacit craft skill of instantiating their expertise in practice:

> It's a bit of a dark art, you know, rheology. I've been working on rheology for many years now and I'm still learning. I appreciate these different artefacts which come in to rheological measurement for example surface tension, things you haven't appreciated before which can make slight inconsistencies in your measurement, inaccuracies and things… The thing is, with rheometers anyone can come along, put a sample in, do a measurement – what comes out of it might be rubbish. You need to programme a rheometer precisely to get the information which you want and is correct. And that is the 'dark art' if you like.

Expert-networks are replete with tacit knowledge with each discipline having its own articulated in a distinct way. It is a key element of why gaining interactional or contributory expertise is so difficult, and why expert-networks can function to reinforce identity work around existing boundaries as opposed to break them down.

As noted above, almost all the disciplinary exchange points across the expert-network involved knowledge or materials, meaning they involved only interactional expertise. However, there was one distinct example in which a scientist was required to take on a level of tacit knowledge and contributory expertise from another discipline in order to deliver their work. This involved a rheological engineer active in work packages two and three who needed to conduct some basic tasks from cell biology. Essentially, they needed to keep murine lipid cells alive for one-to-two weeks in order to conduct their experiments with the bio-rheometer. This requirement involved successfully conducting only basic cell culturing tasks, and in no way constitutes the full contributory expertise of designing, conducting, and publishing complete cell biology research projects. Yet, as this example shows, the attainment of even limited contributory expertise required significant labour and support from across the expert-network.

Around three months into the project the rheological engineer, based at the City 2 site, made repeat visits to a cell biologist in City 1 over several months, first to watch, and then repeatedly conduct, the basic work of passaging (growing and splitting) cells. It was a disciplinary exchange point of knowledge and practice, which occurred in preparation for cell passaging in City 2 during rheological experiments. Due to the work required to prepare the rheometer, it was around a year later before the engineer needed to commence the cell work. Two things happened in this time. Firstly, the engineer became more distant to their training. Secondly, the first cell biologist on the project left the expert-network for personal reasons and was replaced by a new cell biologist. When it became time for the experiments to begin the new cell biologist produced a stock of cells for the rheologist to use as they re-immersed themselves in the practice of cell culturing. At one point, they faced a problem when the cells would not grow on the metal petri dish designed for the rheometer, so they decided to use a standard tissue culture petri dish instead. However, again, the cells would not grow and the engineer could not ascribe why. Detailing the problem, and its solution, the engineer explained:

> I think one example of where my lack of experience might have cost us a little bit of time, talking about a few weeks, is that when the metal petri dish on the rheometer about didn't work. For whatever reason, the cells weren't happy with this metal petri dish on the bottom of the rheometer… So we decided to go back to just using a standard tissue culture petri dish on the rheometer. We found a method of making sure that it was flat on the rheometer and it wasn't a problem, and that's the technique we use now, just a standard tissue culture petri dish. But after several attempts I could not get the cells to grow on the rheometer in these petri dishes, on the rheometer or in the incubator... And it turned out in one of the consortium meetings when I mentioned this, somebody put their hand up and said, "Are you using bacteriological-grade petri dishes?" I said, "*Well I haven't got a clue." I didn't know there were two different types*. [Emphasis added]

This example again highlights the significance of the three-monthly project meetings. Many potential causes were considered during this discussion before a cell biologist asked whether the engineer was using bacteriological grade petri dishes. As apparent in the extract, the engineer was not aware petri dishes came in different types, and had simply used the dishes available, which did, in fact, turn out to be bacteriological grade and thus would never support sufficient adherence for the cells to grow. Here we see an example of tacit knowledge in that the use of the correct type of petri dish was such a taken-for-granted given by the cell biologist that it was not even shared with the engineer until after several weeks of unsuccessful culturing (see also Stephens et al., 2018). The role of geography here was not lost to this cell biologist:

> One of the most difficult things with the collaboration with [the engineer] is actually, strangely enough, that they are in City 2. Yes, we can have meetings. We can go down. We can talk over the phone. But being able to walk down the corridor and say, "you're using the wrong plates, do you know that?" would have saved us weeks of time.

Once passaging commenced the engineer needed to confirm the cells were 'happy'. Initially this involved emailing photographs of the cells to the cell biologist for confirmation, before the engineer could recognise on their own that these wild-type fibroblast cells are 'happy' when they look star-shaped or bi-polar, while 'unhappy' or dead cells look more like a ball. This ongoing learning process extended to the engineer autonomously retrieving and implementing the manufacturer's protocol for the nucleus stain DRAQ7 to identify when cells were dead or not, although the rheological engineer noted they could only have done this because the cell biologist suggested it, as they were not aware of the dye before being prompted.

Here we have seen multiple disciplinary exchange points as the cell biologist and engineer share ideas, opinions, materials, and practices. It resulted in the engineer being able to conduct a set of basic cell biology procedures with a level of confidence and competence. However, it is vital to note that the engineer's contributory expertise in cell culturing operated only across a limited set of procedures and remained highly dependent upon sustained disciplinary exchange points with established cell biologists who work to support and scaffold the engineer in acquiring a tacit knowledge-based skill set and troubleshooting problems. Despite these challenges, the end result pleased the cell biologist involved enough for them to describe the work as "really neat, cross-disciplinary experiments, really truly". Given this success, the example still works to show that it is difficult to share full contributory expertise across an expert-network.

Managing and reconfiguring the expert-network

A key task of the project life cycle was keeping the expert-network together and retaining its focus upon successful outcomes. Like many research efforts, the project was challenged by (i) some experiments providing less successful outcomes than anticipated (e.g. the non-natural amino acids and the MRI work), and (ii) changes in the personnel within the expert-network as some people left (through a diverse set of professional and personal circumstances) and new people joined. The reconfiguration of the expert-network both shaped, and was shaped by, the successes and challenges of the consortium. In some instances the replacements were 'like-for-like' (as in the employment of a new cell biology PDRA to replace the existing cell biology PDRA who left the consortium for personal reasons), in others they were not direct replacements (as in the discontinuation of the non-natural amino acid work when the lead researcher relocated to another University), and in others new people joined bringing new expertise as new disciplinary exchange points entered the network (as with the bioinformatician who joined the consortium after it had commenced its work).

Reflecting upon first an instance of replacement, and then one of no replacement, the PI (and second author on this paper) articulated in an interview towards the end of the project:

> when [cell biologist 1] left and [cell biologist 2] joined, [cell biologist 2] was very capable and was able to get out there and talk to people and chase people and hassle them. I think when the non-natural amino acids expert left… I think at that stage we probably worked out that we weren't going to get it to work anyway. So that was less disruptive.

Success here is defined relative to sustaining and shifting research goals for the consortium as a whole, and the disciplinary groups within it. In the cell biology case, the communicative capacity of the new researcher to engage with those already in place was deemed key to the successful replacement. The switch from non-natural amino acids, in contrast, was dealt with by reconfiguring the network's research plans.

There were also cases of personnel shifting within the consortium and focusing upon a new area of expertise and new goals (e.g. moving focus from MRI to PET). This example repays further examination. In the initial research proposal, one team member – a chemist based in the University MRI scanning facility – was included to work on non-invasive MRI of the trackers for cell lines produced by the non-natural amino acids team and on using Chemical Exchange Saturation Transfer (CEST) for live cell imaging. These elements of the overarching project encountered technical difficulties and neither could be made to work, as described by the chemist involved:

> we were hoping that these non-natural amino acids would be really good for MRI imaging. But unfortunately, MRI is a fairly insensitive imaging methodology in terms of being able to pick up injected tracers, but there's just no way, the technologies just don't meet in the middle. There's no way you can make an MRI sensitive enough to pick up the levels of proteins with non-natural amino acids the technology could produce. And there's also no way that the non-natural amino chemists could bump up the amount of protein produced to sort of match the MRI insensitivity. So, unfortunately, there's a little gap in the middle that meant those two technologies wouldn't really meet.

As this was becoming apparent, organisational issues also arose because, as just noted, the lead of the non-natural amino acids team relocated to a different (overseas) University, and the overarching University funding for the MRI support team was downsized. Subsequently the chemist became based in the University's PET centre. This necessitated further reorganisation of the expert-network, and with it, some research activities within the project. Unlike the cell biology staff change, a 'like-for-like' replacement was not deemed necessary, as the MRI work had proved unsuccessful. Instead, the chemist continued to contribute to the project in their new role by exploring PET tracking, which made an unexpected yet productive contribution to the project and those designed to follow it, as articulated by the cell biologist who was PI on the project (and second author on this paper):

> It actually made it slightly easier for me, that changing of position, because s/he ended up being [physically situated on the same campus]. So I could meet with them and talk to them a lot more readily… And it turned out absolutely to be more beneficial because they went from working with [the MRI centre] where we were doing some work, mostly related to the CEST, which then subsequently didn't work, obviously. Then the move opened up the avenue for PET. So that was actually a fortuitous move. I'd like to say planned (laughter), but unfortunately not.

In terms of the micro-organisation of work, this example shows how managing the project involved the curation, maintenance, and creative reconfiguration of the expert-network in response to the (often unanticipated) circumstances that arose. Such practices can be necessary in any team-based work, but take a specific form in interdisciplinary expert-networks where maintaining or creatively reconfiguring disciplinary exchange points remains important.

Discussion: Learning points for STS and interdisciplinary practitioners

> *So it's difficult to do*, interdisciplinary science. What you want to try and do is you want to try and manage the people so that they feed into each other but they don't necessarily overlap. And the reason why I'm saying that is because they have to learn a whole new bunch of skills. Now, you could argue that's a good idea, *but that takes time*, and it's more than a three-year grant allows. [Emphasis added]

The above quotation is from the final interview conducted in the project with the consortium PI (second author on this paper). It shows the aspiration of interdisciplinary work, as well as the real-world constraints, and captures the value of the expert-network framework. While the project had successes, the consortium did not achieve all it set out as some aspects failed (CEST and non-natural amino acids) and other aspects did not achieve all that was proposed in the timeframe available (rheology and CARS). This given, it did achieve some things it had not originally planned, as the expert-network was reconfigured.

In this paper, we have sought to understand how the consortium operated as an interdisciplinary group by articulating and demonstrating empirically the notion of the expert-network. An expert-network is a set of managed relationships between one or more disciplinary groups who are collaborating towards a broadly shared goal. Within the expert-network, researchers retain expert status in their own discipline, premised upon trust relationships and demonstrations of ability, and make ongoing judgements about how much of the technical detail of their expertise needs to be shared with others, and how much of others' technical expertise they need to learn. As such, the expert-network is sustained by ongoing negotiation and mutual trust.

We suggest the notion of an expert-network is valuable in two contexts: first, that it is useful for social scientists seeking to analyse interdisciplinary groups, and second, that it is useful for those conducting interdisciplinary work to make sense of their context and its management. On the first point, we argue the expert-network notion provides an analytically productive social science perspective on understanding how interdisciplinary work operates when researchers from different disciplines collaborate. It leverages insight into how disciplinary exchange points facilitate movement of materials, knowledges, and sometimes practices between expert groups, while also allowing these expert groups to retain, and in some regards, reinforce, singular disciplinary identities. Equally the recognition of potential reshaping within the expert-network captures the interrelatedness of issues such as the personal life choices and challenges of members of the network (who may leave or adopt a new role) and the permeability of the network as new members join, and bring with them new perspectives on existing disciplinary roles, or entirely new areas of expertise. In this way, the expert-network accounts for both the potential flexibility and stability of disciplinary teamwork. As an analytical framework, the expert-network also shows how hard interdisciplinary work can be to accomplish. This can be both due to the tacit component of interactional and contributory expertise that requires time, immersion, and scaffolding to transfer, and to the affective and lived experience of all human interaction here framed in an interdisciplinary context.

The distinctiveness of the expert-network concept - in the context of the existing work on interdisciplinarity noted earlier - comes through the relationship between six components, none of which are unique on their own, but bring value and novelty in their interrelation. The first is that our use of the expert-network concept does not seek to define interdisciplinarity or delineate it from other modes of practice, but instead thinks through how interdisciplinarity is enacted by practitioners operating under its name. The second is the focus on the relatedness and non-relatedness of material, knowledge, and practice exchanges, with the novelty compared to some other approaches to interdisciplinarity specifically found in the focus upon material elements of group work. The third is the inherent recognition within the expert-network concept of the fluid and non-static capacity of interdisciplinary work, capturing how ideas, goals, and relationships can (and perhaps should) shift. By accommodating change over time, and embedding it within the account, our concept enables analysis of altering network make-ups, and how disciplinary exchange points are maintained or reconfigured over time. The fourth is the inclusion of disciplinary identity work, and by extension the potential study of power (cf. Stephens et al., 2018), that this concept facilitates, recognising participants as lived-beings with experiences and demands beyond the expert-network that shape practice. The fifth component, quite simply, is the simplicity of the concept itself, making it amenable to application by analysts and practitioners. The sixth, and final, component of its distinctiveness is its integration into the SEE framework, both providing the expert-network approach with further intellectual grounding, and contributing to further elaborating SEE itself.

As noted above, none of the components are unique within the interdisciplinarity literature alone. Resisting singular definitions of interdisciplinarity is found in Jacobs and Frickel (2009) and to a lesser extent in Barry, Born, and Weszkalnys (2008). Osbeck and Nersessian (2010) and Morrison (2017) also draw our attention to materiality in addition to knowledge and practice. MacLeod and Nagatsu (2018) show that disciplinary interactions can shift overtime, with their focus upon crystallisation on integrative platforms showing how expert-networks can, eventually, become stabilised in context specific ways. Multiple authors have pointed to interdisciplinary contexts as sites of power (Stephens et al., 2018; Callard and Fitzgerald, 2016; Albert et al., 2016), while Callard and Fitzgerald (2016), as well as Osbeck and Nersessian (2010) also make explicit the identity and emotionality of such experiences. Finally, Gorman (2002), Andersen and Wagenknecht (2013), and Osbeck and Nersessian (2010) draw upon the SEE framework in some regards within their work. However, in its totality, the expert-network approach configures these elements in a form that potentially yields value for others who creatively deploy the concept in novel contexts and novel ways.

The expert-network concept is rooted in the analysis of this single case, and the intended utility driving it is to illuminate the work of this specific consortium. This given, it could have applicability beyond this specific context, specifically because of its flexibility. Clearly, not all interdisciplinary groups operate in the same way (Fiore, 2008; Huutoniemi et al., 2010), yet the focus upon a non-static network that can be reconfigured and required maintenance is likely to prove valuable in contexts different to the one specified here. Subsequent application in additional contexts could further strengthen the analytical breadth and robustness of the expert-network approach as other variables and insights could be incorporated. Indeed, further learning could even be gained from analysts' experiences in which their specific setting proves ill-suited to an expert-network mode of analysis. This aim here is not to assert which contexts the expert-network framework is or is not well suited, but to offer it as a possibility for others to consider.

As such, the expert-network conceptualisation makes a contribution to social science analyses of scientific practice. It provides a model for subsequent STS researchers to analyse other examples of interdisciplinary work. If doing so, the researcher should map the contributory and interactional expertise across the network, and document the intended and actual flows of knowledge, materials and practice, and the disciplinary exchange points through which these occur. The analyst can then identify in what form any interactional expertise or interlanguage formation occurs (if any) and describe the practices that support this, as well as the judgements as to when researchers believe they know 'enough'. Linked to this, it is also valuable to identify when and how tacit knowledge and the challenges in exchanging it frame the expert-network's practice. Finally, the analyst should document changes in the network overtime, and document how the curational and maintenance work is accomplished. Corollary to this, the notion of the expert-network developed here also contributes to the SEE framework by providing a mechanism by which it can be applied to assessing interdisciplinary research projects.

The second reason we suggest the notion of the expert-network is valuable is for framing thinking about the conduct of interdisciplinary work, and informing its management. By encouraging those engaged in collaborative projects with multiple expertises to consider themselves part of an expert-network, and the implications this brings, we hope the experience and productivity of doing such work can be increased. Subsequently, in closing this paper we contribute to this by articulating some learning points for those managing interdisciplinary teams that reflect upon the experience of the project described through our expert-network approach. This is specifically from the perspective of the project Principle Investigator, P. Stephens, summarising key learning points from the consortium and the engagement with the expert-network concept, in order to offer advice to like-minded colleagues. These points address the overlapping themes of management and leadership, interdisciplinarity, flexibility and logistics:

Management and leadership:

- A well thought out project plan by the Principle Investigator is beneficial from the start, as managing large projects requires someone with the overall vision and clarity of thinking across, what are often, quite disparate research disciplines. This plan would benefit from mapping the expert-network, and making explicit the disciplinary exchange points where knowledge, materials and practice cross disciplinary borders.

- A Principle Investigator on a large grant does not need to be a contributory expert in all disciplines involved. Instead it is valuable to ensure contributory expertise to all the disciplines involved exists in the project through the Co-Investigators.

- Principle Investigators should not seek to overly direct the work of others, but should instead believe in the Co-Investigators. Micro-managing all elements of the project is unlikely to make for a successful collaboration or outcome. The trust upon which this is based is best formed through interpersonal interaction, and ideally, this will be in place before the research proposal is submitted.

Interdisciplinarity:

- Working across disciplines is challenging, especially across biological and physical sciences, as each discipline has its own technical language. Creatively producing a shared set of terms and references that respond to the specific context of the disciplinary mix and project goals is productive for developing the interactional expertise across the project that fosters improved understanding.

- Training people to work across disciplines is also challenging, especially when dealing with disciplinary tacit knowledge. This is knowledge that is crucial in order for something (e.g. an experimental protocol) to work properly, but is difficult to effectively communicate to someone else over the short period of time that is associated with a research grant.

- Learning contributory expertise in a new discipline requires a significant investment of time. It is possible to pass on limited practical experience – such as the rheological engineer who could conduct certain cell culturing procedures – but it requires ongoing support and scaffolding from an established contributory expert.

- In practice, the expert-network can reinforce disciplinary boundaries within an interdisciplinary team more so than break these boundaries down because contributory experts remain authorities within their specialisation with limited engagements funnelled through the disciplinary exchange points.

Flexibility and logistics:

- Being clear about risks in the planning and communication with project members is important. Principle Investigators should have the confidence to re-direct research (mid-project) to other areas if needed to ensure a successful overall outcome.

- Meeting physically and regularly as a project team improves understanding and builds trust relationships. The project reported here found three-monthly intervals valuable, but other projects with different timelines or geographical contexts may opt for a different cycle.

- If research personnel need to change it is best to view this positively as new people bring new expertise and new insight. Hence, embrace the flexibility of the expert-network, but continue to retain an up-to-date plan that makes clear the disciplinary exchange points where knowledge, materials, and practices pass between disciplines.

- Principle Investigators should not underestimate the time needed to commit to running the wider project and making it a success. Often the Principle Investigator has to deal with not only scientific matters but also personnel ones in order to ensure a smooth running of the overall project, and these personnel matters can themselves reshape the expert-network.

To conclude, interdisciplinary research is both challenging and productive. By recognising the different skills and knowledges across a project as an expert-network the research team can identify risks and scope for flexibility. In so doing, project teams can discover more about the practicalities of interdisciplinarity, as well as discover more about their science. As a framework for the social scientist, the notion of an expert-network offers a perspective on analysing detailed datasets on interdisciplinary cooperation in practice.

Acknowledgements

We would like to thank the other consortium members for participating in this research. We acknowledge the funding of the EPSRC(UK) for supporting the work (grant EP/H045848/).

References

Albert M, Paradis E and Kuper A (2016) Interdisciplinary fantasy: Social scientists and humanities scholars working in faculties of medicine. In: Frickel S, Albert M and Prainsack B (eds) *Investigating Interdisciplinary Collaboration*. New Brunswick, NJ: Rutgers University Press, pp. 84-103.

Andersen H and Wagenknecht S (2013) Epistemic dependence in interdisciplinary groups. *Synthese* 190(11): 1881-1898.

Barry A, Born G and Weszkalnys G (2008) Logics of interdisciplinarity. *Economy and Society* 37(1): 20-49.

Brew A (2008) Disciplinary and interdisciplinary affiliations of experienced researchers. *Higher Education* 56(4): 423-438.

Bruun H and Sierla S (2008) Distributed problem solving in software development: The case of an automation project. *Social Studies of Science* 38(1): 133-158.

Callard F and Fitzgerald D (2016) *Rethinking interdisciplinarity across the social sciences and neurosciences*. Basingstoke: Palgrave Macmillan.

Calvert J (2010) Systems Biology, Interdisciplinarity and Disciplinary Identity. In: Parker JN, Vermeulen N and Penders B (eds) *Collaboration in the New Life Sciences*. Surry and Burlington: Ashgate, pp. 201-218.

Cassidy A (2016) One Medicine? Advocating (Inter) disciplinarity at the interfaces of animal health, human health, and the environment. In Frickel S, Albert M and Prainsack B (eds.) *Investigating Interdisciplinary Research: Theory and Practice across Disciplines: Theory and Practice across Disciplines.* New Brunswick, NJ: Rutgers University Press, pp. 213-236.

Centellas K, Smardon R and Fifield S (2014) Calibrating translational cancer research: Collaboration without consensus in interdisciplinary laboratory meetings. *Science, Technology and Human Values* 39(3): 311–335.

Collins H (2010a) *Tacit and Explicit Knowledge*. Chicago: University of Chicago Press.

Collins H (2010b) Tacit knowledge: you don't know how much you know. *New Scientist* 206(2762): 30-31.

Collins H and Evans R (2015) Expertise revisited, Part I—Interactional expertise. *Studies in History and Philosophy of Science Part A*. 54: 113-123.

Collins H and Evans R (2007) *Rethinking Expertise*. Chicago: University of Chicago Press.

Collins H, Evans R and Gorman M (2007) Trading Zones and Interactional Expertise. *Studies in History and Philosophy of Science* 38(4): 657-666.

Cuevas-Garcia CA (2018) Understanding interdisciplinarity in its argumentative context: thought and rhetoric in the perception of academic practices. *Interdisciplinary Science Reviews* 43(1): 54-73.

Dogan M and Pahre R (1990) *Creative marginality: Innovation at the intersections of social sciences*. Boulder: Westview Press.

Duarte TR (2017) Mutual Linguistic Socialisation in Interdisciplinary Collaboration. In: Reyes-Galindo L and Duarte TR (eds) *Intercultural Communication and Science and Technology Studies*. Cham: Palgrave Macmillan, pp. 55-78.

Fiore SM (2008) Interdisciplinarity as teamwork: How the science of teams can inform team science. *Small Group Research* 39(3): 251-277.

Frickel S, Albert M and Prainsack B (2016) *Investigating interdisciplinary collaboration: theory and practice across disciplines.* New Brunswick NJ: Rutgers University Press.

Fujimura JH (1987) Constructing 'Do-able' Problems in Cancer Research: Articulating Alignment. *Social Studies of Science* 17(2): 257-293.

Galison P (1996) Computer simulations and the trading zone. In: Galison P and Stump DJ (eds) *The Disunity of Science: Boundaries, Contexts, and Power*. Stanford: Stanford University Press. pp. 118-157.

Goddiksen M (2014) Clarifying interactional and contributory expertise. *Studies in History and Philosophy of Science Part A* 47: 111-117.

Gorman ME (2002) Levels of expertise and trading zones: A framework for multidisciplinary collaboration. *Social Studies of Science* 32(5-6): 933-938.

Gorman ME and Spohrer J (2010) Service science: A new expertise for managing sociotechnical systems. In: Gorman M (ed) *Trading zones and interactional expertise: Creating new kinds of collaboration.* Cambridge MA: MIT Press. pp. 75-105.

Graff H J (2016) The "problem" of interdisciplinarity in theory, practice, and history. *Social Science History* 40(4): 775-803.

Huutoniemi K, Klein JT, Bruun H and Hukkinen J (2010) Analyzing interdisciplinarity: Typology and indicators. *Research Policy* 39(1): 79-88.

Jacobs JA (2014) *In defense of disciplines: Interdisciplinarity and specialization in the research university*. Chicago: University of Chicago Press.

Jacobs JA and Frickel S (2009) Interdisciplinarity: A critical assessment. *Annual review of Sociology* 35: 43-65.

Klein J and Newell W (1998) Advancing Interdisciplinary Studies. In Newell W (ed) *Interdisciplinarity: Essays from the literature*. New York: College Board, pp. 3-22.

Klein J (1990) *Interdisciplinarity: History, theory, and practice*. Detroit: Wayne state university press.

Lewis J and Bartlett A (2013) Inscribing a Discipline: Tensions in the Field of Bioinformatics. *New Genetics and Society* 32(3): 243–263.

Lewis J, Bartlett A and Atkinson P (2016) Hidden in the middle: culture, value and reward in bioinformatics. *Minerva* 54(4): 471-490.

Lyall C, Bruce A, Marsden W and Meagher L (2013) The role of funding agencies in creating interdisciplinary knowledge. *Science and Public Policy* 40(1): 62-71.

Madsen D (2018) Epistemological or Political? Unpacking Ambiguities in the Field of Interdisciplinarity Studies. *Minerva* 56(4): 453-477.

Meskus M (2018) *Craft in Biomedical Research: The iPS Cell Technology and the Future of Stem Cell Science*. New York: Palgrave Macmillan.

Mody CC (2016) An electro-historical focus with real interdisciplinary appeal': Interdisciplinarity at Vietnam-era Stanford. In: Frickel S, Albert M and Prainsack B (eds) *Investigating Interdisciplinary Collaboration*. New Brunswick, NJ: Rutgers University Press, pp. 173-193.

Morrison M (2017) "A good collaboration is based on unique contributions from each side": assessing the dynamics of collaboration in stem cell science. *Life Sciences, Society and Policy* 13(7) 1-20.

NAS (2005) *Facilitating Interdisciplinary Research*. Washington, DC: National Academies Press.

Nersessian NJ and Newstetter WC (2014) Interdisciplinarity in Engineering Research and Learning. In: Johri A and Olds B M (eds) *Cambridge handbook of engineering education research*. Cambridge: Cambridge University Press, pp. 713-730.

Newell WH, Szostak R and Repko A (2008) The Intertwined History of Interdisciplinary Undergraduate Education and the Association for Integrative Studies: An Insider's View. *Issues in Interdisciplinary Studies* 26: 1-59.

Nissani M (1997) Ten cheers for interdisciplinarity: The case for interdisciplinary knowledge and research. *The Social Science Journal* 34(2): 201-216.

Nowotny H and Scott P Gibbons (2001) *Rethinking science: Knowledge and the public in the age of uncertainty*. Cambridge: Polity Press.

Osbeck L and Nersessian N (2010). Forms of positioning in interdisciplinary science practice and their epistemic effects. *Journal for the theory of social behaviour* 40(2): 136-161.

Parker JN, Vermeulen N and Penders B (2012) *Collaboration in the New Life Sciences*. Surry and Burlington: Ashgate.

Riesch H, Emmerich N and Wainwright S (2018) Introduction: Crossing the Divides. In Riesch H, Emmerich N and Wainwright S (eds) *Philosophies and Sociologies of Bioethics*. Cham: Springer. pp. 1-22.

Rossini FA and Porter A L (1979) Frameworks for integrating interdisciplinary research. *Research Policy* 8(1): 70-79.

Stephens N, Atkinson P and Glasner P (2011) Documenting the doable and doing the documented: Bridging strategies at the UK Stem Cell Bank. *Social Studies of Science* 41(6): 791-813.

Stephens N and Lewis J (2017) Doing laboratory ethnography: reflections on method in scientific workplaces. *Qualitative Research* 17(2): 202-216.

Stephens N, Khan I and Errington R (2018) Analysing the role of virtualisation and visualisation on interdisciplinary knowledge exchange in stem cell research processes. *Palgrave Communications* 4(1): 78.

Tomov DT and Mutafov HG (1996) Comparative indicators of interdisciplinarity in modern science. *Scientometrics* 37(2): 267-278.