Relying on Relays. A Socio-technical Integration Model for Interdisciplinary Research

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Abstract

This article proposes a theoretical model for practices of integrating knowledge across disciplines. We characterise it by the sports metaphor of a relay, to highlight the directional interactions that occur in interdisciplinary work when it is organised as a series of exchanges of materials, data, calculations, and models. Drawing on existing research to outline its main features, we develop the model using interviews with and observations of scientists in three biotechnology projects. The article analyses how scientists describe and practice interdisciplinarity, examining the underlying moral economy and their efforts at integration. The sequential exchanges between laps of disciplinary work form the core of the interdisciplinary epistemic machinery in each of the analysed projects. Achieving integration requires alignment through infrastructuring, calibration, and articulation work. The relay model describes a particular socio-material practice of interdisciplinarity. We conclude by discussing its potential and limitations.

Keywords: Interdisciplinarity, Integration, Epistemic machineries, Relay, Articulation work

Introduction: The trouble with 'interdisciplinarity'

Public authorities are increasingly calling for interdisciplinary collaboration to tackle grand social challenges and achieve scientific breakthroughs (European Commission, 2015), thereby presenting interdisciplinarity as a panacea in science policy. However, as Freeth and Vilsmaier (2020: 58) observe, there is a "tension between assumptions on the one hand that interdisciplinary collaboration can address the complexity of contemporary research questions and thus deserves considerable investment of time, effort and funds and, on the other hand, the myriad barriers and uncertainties faced when engaging in such collaborations." The diversity of definitions, the prevalence of normative scholarship, and the challenges of translating theory into practice reinforce this tension (Frickel et al., 2017). Therefore, "we need further research into the inside, lived experiences of interdisciplinary collaboration" (Freeth and Vilsmaier, 2020: 58). This article empirically studies such cooperation, highlighting knowledge integration practices across STEM disciplines.

Since definitions of interdisciplinarity are plentiful, unambiguous identification becomes challenging (Huutoniemi et al., 2010; Klein, 1990, 2010). Weingart (2000: 30) describes the paradox of defining interdisciplinarity by highlighting that "(t)he discourse on interdisciplinarity is, in effect, a discourse on innovations in knowledge production". As a point of departure, this article regards 'interdisciplinarity' as an umbrella concept that encompasses various integrative research practices, aligning with much of the existing scholarly literature. Pragmatically, we learn about interdisciplinarity by analysing the epistemic practices that scientists assert to be interdisciplinary.

The issue we explore is the practice of integrating materials, data, and knowledge in interdisciplinary research that provides new insights that transcend disciplinary and professional boundaries. Some scholars have devoted considerable attention to such efforts, which they consider a defining quality of interdisciplinarity (Klein, 2012; Laursen and O'Rourke, 2019; Pohl et al., 2008). This focus contrasts with contributions primarily addressing the obstacles to interdisciplinary collaboration. Such obstacles include institutional barriers and a lack of institutional support (Boden and Borrego, 2011; Brandt et al., 2013; Lyall, 2019; Weingart and Padberg, 2014), proximity barriers (cognitive and geographical distance) (Rekers and Hansen, 2015; MacLeod and Nagatsu, 2018; Nersessian, 2019; Vermeulen, 2019), communication barriers (Bracken and Oughton, 2006; Monteiro and Keating, 2009; Galison, 2010; Klein, 2010), and disciplinary barriers arising from the hegemony of scientific disciplines concerning socialisation, problem choice, publishing, and careers (Lyall, 2019; Woiwode and Froese, 2021).

Some scholars employ cartographic metaphors, including boundary crossing (Klein, 1996), borderlands (Strathern, 2004), and boundary objects (Star and Griesemer, 1989), to suggest how obstacles can be managed. These contributions are significant, but such emphasis on boundaries may position interdisciplinary efforts at the periphery of disciplines rather than asking how such practices are constituted (Sørensen, 2021). Analysing integration might be a remedy, but what does that imply?

Several relevant contributions explore the dynamics of interdisciplinary research and, consequently, address issues of integration. Bruce et al. (2004) emphasise the importance of assembling teams and identifying ways to communicate across disciplines. Clearly, collaboration is a vital aspect of interdisciplinarity (Brown et al., 2015; Freeth and Vilsmaier, 2020; Halfon and Sovacool, 2023; Leahey, 2016), and many scholars are concerned with the objectives of such cooperation. They tend to highlight the role of the humanities and social sciences in elucidating the social and ethical dimensions of the research. Fisher et al. (2015) review various approaches to this end. One example is socio-technical integration research that seeks to make scientists more socially accountable (Smolka, 2020; Åm and Sørensen, 2015). Such efforts may lead to diverse roles for humanities and social science scholars (Kocksch and Sørensen, 2023), who, nonetheless, may struggle to have their expertise recognised (Balmer et al., 2015).

This article aims to go beyond highlighting reflexivity and cognitive issues to empirically investigate integration practices, based on an understanding of interdisciplinary integration as socio-material practices designed to facilitate the movement and management of materials, data, and knowledge within interdisciplinary research (Boix Mansilla et al., 2015). Integration may also include efforts to promote scientists' social accountability (Smolka, 2020; Åm and Sørensen, 2015). In the following section, we will draw upon insights from science and technology studies (STS) and previous studies on interdisciplinarity to outline the essential features of a model for organising integration efforts, which we refer to as *the relay model*, thus using a sports metaphor that highlights exchanges where laps of effort are connected. The emphasis on exchanges is a vital characteristic of the model. However, it is not meant to describe all forms of integration practices. We shall return to the limitations.

The following section outlines the model's basic features. It serves as a starting point for further elucidation of the concept through an empirical study of three research projects at a Norwegian biotechnology research centre.

Socio-material integration in interdisciplinary research: The basic physiology of the relay model

Existing scholarship highlights various methods for achieving integration in interdisciplinary research. For example, Klein (2012) points to language, concepts, and models as essential tools, while Pohl et al. (2006) identify four primary means of integration: (1) mutual understanding, (2) theoretical concept, (3) model, and (4) product. Furthermore, several scholars emphasise modelling. Nersessian (2019) exemplifies this cognitive approach by describing how scientists constructed and manipulated physical simulation models to bridge the gap between engineering and biology. MacLeod and Nagatsu (2018) and Turnhout (2019) find modelling an essential integration tool in interdisciplinary environmental science. However, Turnhout also mentions other cognitive instruments, such as scenario approaches and cost-benefit and multicriteria analyses. In this manner, she emphasises the benefits of using conceptual frameworks to link different types of information or knowledge.

The relay model may include such integration methods, but it is developed to observe socio-material practices related to exchanges between project participants. For example, Bucciarelli (1994) emphasises the importance of negotiations, material constraints, and affordances. Negotiations may involve epistemic standards, trust and reliability, coordination of expertise, and distribution of tasks (Calvert and Fujimura, 2011; MacLeod et al., 2019; Siedlok et al., 2015).

However, the success of integration efforts relies on how the collaboration of scientists is organised. Scholars have identified several methods to manage such collaboration (Defila and Di Guilio, 2015; Andersen and Wagenknecht, 2013; Bruun and Sierla, 2008). The relay model is one such method that emphasises sequential exchanges between discipline-based groups of scientists. This mode of organisation shapes the collaboration to focus on the conduct of exchanges of, e.g., materials and data (Leonelli and Tempini, 2020; MacLeod and Nagatsu, 2018; Nersessian, 2019). Such exchanges may not be singular and unchanging but rather "simultaneously engaged in many different relations" related to "multiple interrelated infrastructures enacted through different practices" (Hoeyer et al., 2017: 389). How can we understand such efforts to transcend disciplines?

As a start, we may notice that disciplines can be viewed as social worlds, i.e., universes of discourse (Strauss, 1978). Therefore, following Stephens and Stephens (2021), we can understand the integration challenge that the relay model addresses as the need to manage the relationship between the disciplinary social worlds of the scientists involved in providing and receiving materials, data, calculations, and knowledge through exchanges. Kruse (2021) offers further insights into the flow of materials and knowledge within the Swedish criminal justice system. She views the system as comprising several professions, each with its own distinct epistemic culture that shapes how a scientific community creates, validates, and disseminates knowledge (Knorr Cetina, 1999), prompting an analysis of the meaning and practices of knowledge-making. In her case, Kruse also employs a relay metaphor to describe how forensic evidence is transferred between epistemic cultures. In this context, the knowledge objects must remain stable when moved between epistemic cultures. Alongside Vertesi (2014), Kruse identifies seams between the social worlds within the system, which possess differing knowledge-making infrastructures and specific standards that necessitate what she refers to as alignment work, which are efforts to bridge infrastructures and standards through infrastructuring.

We anticipate that interdisciplinary research will differ from Kruse's case, as strict stabilisation may not be necessary, or even possible, in research projects, and stringent standards for exchanging materials, data, and knowledge may not exist. Consequently, our relay model will differ, and we aim to clarify these differences. Nevertheless, we view the efforts in the project to facilitate the movement of knowledge objects from one social world to another as locally contingent alignment and articulation work. This assumption requires us to specify such practices and their consequences. While Kruse considers alignment work to involve infrastructuring efforts to stabilise forensic knowledge objects, we argue that the exchanges between the social worlds of disciplines in an interdisciplinary project will necessitate inventions. First, it will require what Strauss (1978) calls 'articulation work', which involves efforts to make the differences between the social worlds visible and manageable, thereby enabling exchanges between them. In our analysis, the main ingredient is the development of practices of interdisciplinary communication to present and make sense of results.

Second, the required alignment work may involve socio-material endeavours to provide the necessary media for transporting materials, data, and knowledge, suitable to the project context. These efforts, such as data formats, must be calibrated to be effective. Identities, disciplinary commitments, and group participation customs must be continuously negotiated because meanings are fluid, contextual, and relational. For example, project meetings may serve as calibration events where researchers can check their interpretations of exchange practices (Centellas et al., 2014). Thus, interdisciplinary integration is conducted through what Knorr Cetina (1999) refers to as 'epistemic machineries' – the tools, artefacts, institutional arrangements, as well as specific strategies, visions, and procedures that, within a field of expertise, "make up how we know what we know" (Knorr Cetina, 1999: 1). Epistemic cultures possess distinct epistemic machineries, as Silvast and Foulds (2022) illustrate by emphasising the significance of diverse modelling approaches in their study of interdisciplinary energy research. Within an interdisciplinary project, each disciplinary social world has its distinct epistemic machinery; however, the entire project necessitates an epistemic machinery that facilitates interdisciplinarity. We assume that the relay model is an exemplar of such machinery.

Most scientists have completed disciplinary training, which shapes their work and professional outlook (Wolwode and Froese, 2021). The resulting differences between the epistemic cultures involved in an interdisciplinary project may create tensions (Broto et al., 2009), which can be alleviated through epistemic interdependence among collaborating scientists (Andersen and Wagenknecht, 2012; Nersessian, 2019), including interdisciplinary communication. Thus, we should ask: how can such communication be achieved? What methods of articulation work can we expect to observe in projects organised according to the relay model?

One such method is to utilise tools such as boundary objects, which are elements employed in two or more social worlds that facilitate communication between them (Fujimura, 1992). Galison (2010) proposes understanding knowledge exchanges across disciplines as facilitated by shared linguistic practices arising from the development of interlanguages such as jargon, pidgin, and creole. In this way, Galison highlights the significance of linguistic skills. Collins and Evans (2007) share this emphasis in their concept of 'interactional expertise'. It refers to "a deep sharing of discourse" (Collins and Evans, 2007: 53), which scientists should learn to participate in constructive discussions across disciplinary boundaries. Lamont (2009) identifies yet another relevant skill to facilitate interdisciplinary communication. She calls it 'cognitive contextualisation', a pragmatic awareness of disciplinary differences and shared rules of deliberation. Therefore, when empirically studying relay model practices and the articulation work involved, we should investigate the types of communication tools and skills incorporated into the interdisciplinary efforts we analyse. The above review suggests that in our analysis, we should look for linguistic resources such as interlanguages (Bracken and Oughton, 2006; Galison, 2010; Monteiro and Keating, 2009).

The existing scholarly literature offers limited insights into the material tools that may facilitate the movement and exchange of materials, data, and knowledge in relay-organised interdisciplinary research. However, Kruse (2021) and Vertesi (2014) provide significant insights by highlighting the role of various forms of infrastructure, including computer networks. In our study, we examine these material aspects of alignment work. Another issue that requires attention is the role of shared values and preferences (Boix Mansilla et al., 2016). Some scholars have emphasised the importance of the emotional dimensions of interdisciplinary collaboration, such as mutual liking and the formation of friendships, and there may even be productive affective tensions (Hesjedal, 2023; Hillersdal et al., 2020; Smolka et al., 2021).

This article explores how the interviewed biotechnology scientists understand, assess, and value interdisciplinarity. Evidently, interdisciplinary collaboration is a formal goal of such projects; however, this does not guarantee positive engagement. Furthermore, we expect that a shared understanding of what is involved in such collaboration and its potential benefits will be incorporated into the epistemic machinery of the interdisciplinary research (Kaplan, 2011). We will analyse this aspect of the relay model by drawing on Daston's (1995) work on moral economies of science to investigate how interdisciplinarity is addressed discursively and affectively. We view the concept of a moral economy as offering a richer perspective on the sense-making of interdisciplinarity and its influence on collaboration than merely observing shared understanding or goals.

Exploring such moral economies involves seeking out webs of "affect-saturated values that stand and function in well-defined relationship to one another" (Daston, 1995: 4), in our case, to analyse the meaning assigned to interdisciplinary work. 'Economy' refers to "an organised system that exhibits certain regularities, regularities that are explicable but not always predictable in their details. A moral economy is a balanced system of emotional forces" (Daston, 1995: 4). Thus, this concept aids in identifying the understanding and valuation of interdisciplinarity as a shared feature that may influence how integration issues are managed within the project, thus serving as an essential ingredient of the epistemic machinery of interdisciplinary. For example, it may support articulation work.

To summarise, this article examines and conceptualises practices of integrating materials, data, and knowledge in selected interdisciplinary projects through sequential exchanges that we refer to as a relay model of interdisciplinary integration. We have outlined the basic features of the model through the above review of relevant scholarship and will utilise our empirical findings to develop the model further. For the model to serve as a starting point for the analysis, we have selected projects organised as directional, multi-step practices for further study. We first explore the projects' moral economy of interdisciplinarity. This serves as a point of departure for analysing the relay practices in each project. We focus on the character of the conducted alignment work, the infrastructuring of the analysed projects to bridge the steps – the relays – within each project, and the articulation work involved in performing the exchanges. We particularly emphasise the communication efforts. Additionally, we examine the calibration efforts that were undertaken. Finally, we discuss how the relay model constitutes an epistemic machinery of interdisciplinarity.

Disciplinary research typically involves relatively stable epistemic practices. However, interdisciplinary projects may need to develop a provisional epistemic machinery to achieve their objectives. Consequently, we may observe different iterations of the relay model, which necessitate discussions regarding the characteristics of the differences and the processes of developing them.

Method

To explore the use of the relay model, we selected projects where we expected to find directed, multi-step exchange practices. Biotechnology seems an appropriate area, since it has been established as an interdisciplinary endeavour involving exchanges between various disciplines. These features make it well-suited for our study. However, all the disciplines in the analysed projects belong to the STEM domain, which may simplify integration compared to research that also involves the humanities and social sciences.

Accordingly, the Centre for Digital Life Norway (DLN), a national biotechnology research network established in 2015, emerged as a promising site. In 2021, the centre hosted 35 research projects, representing a significant investment in Norwegian biotechnology, amounting to approximately 550 million NOK (~ $ 55 million). All DLN projects were required to include a digital component, typically some form of modelling. We selected three projects for further analysis. Although they researched different topics, all were organised as a set of work packages that might require integration through exchanges between them. They were funded from 2016 to 2022 and are hereafter referred to as Projects A, B, and C.

Project A was granted approximately NOK 20 million (~ USD 2 million). It focused on tissue engineering, with scientists investigating how cells thrived in their environments by cultivating them in gels with varying properties to observe how these differences impacted the cells. The project employed high-throughput screening of cell RNA to create a computational model capable of predicting cells' responses to the material properties of their surroundings. It integrated knowledge and methods from engineering (material engineering and analytical technology), life sciences (cell and molecular biology and screening), and mathematical sciences (statistics, bioinformatics, and computational modelling). The research group comprised cell and molecular biologists, bioinformaticians, computer scientists, and engineers.

Project B was awarded NOK 38 million (~ USD 3,8) to investigate environmental toxicology. It utilised Atlantic cod as an indicator of the marine environment and examined how various pollutants, and their combinations, affected the fish. The team consisted of biologists, toxicologists, physiologists, veterinarians, mathematicians, statisticians, and bioinformaticians.

Project C was awarded NOK 40 million (approximately USD 4 million). It examined the mechanisms of brain diseases and their connection to patients' genes. The project was based at a neuroplasticity research centre, aiming to uncover the mechanisms behind the brain's capacity to adapt and learn from experiences. The scientists combined experimental methods with physics-based computational analysis and modelling. Biologists, medical doctors, physicists, mathematicians, and computer engineers collaborated on the project.

Thus, although all the projects had a work package structure, there was considerable topical and organisational diversity. Consequently, we assumed they would engage with integration but also that they would practise the relay model differently, enabling us to observe diverse articulations of the model. Given the need to study processes such as alignment work and moral economies, qualitative methods appeared to be an appropriate research strategy. We opted to combine interviews and fieldwork. Additionally, we have gathered information about project publications through annual reports and the Norwegian Register for Research Publications (https://nva.sikt.no/). We selected this combination of methods to achieve greater heterogeneity and variation in the data (Law, 2004).

The first author interviewed 22 scientists across all three projects and observed centre activities by participating in meetings, conferences, and training workshops. For Projects A and B, she also conducted fieldwork in the labs and during project meetings. The first author analysed and transformed the fieldnotes produced during these observations into a more coherent text, focusing on reflections and empirical examples of emerging topics related to collaboration.

The interviewed scientists were at various stages of their careers: PhD candidates, post-doctoral researchers, laboratory technicians, researchers, associate professors, and full professors. We sought diversity among the interviewees in terms of experience and position, as later-career researchers often possess greater expertise in scientific collaboration than those in the early stages of their careers. Conversely, early-career researchers can provide less biased perspectives. The first author interviewed Norwegian scientists in Norwegian and non-Norwegian speakers in English. Each interview lasted around one hour and was recorded and transcribed verbatim. She utilised a semi-structured interview guide to ask the scientists about the organisation of their research, collaboration, interdisciplinary communication in the project, and their understanding of interdisciplinarity. The fieldwork notes contributed to the development of the guide. The authors have translated Norwegian quotes into English.

We initiated the analysis of the interviews by examining them project by project, initially focusing on responses from each interviewee and subsequently on all interviewees in each project. The interviews were printed in hard copy and analysed by identifying recurring themes and key situations described by the participants. The interviews were then analysed using open coding and memo writing in the coding programme NVivo.

Here, the primary focus was on the scientists' statements, opinions, and arguments regarding collaboration. The codes were subsequently grouped thematically into categories, which were further refined through more focused coding, theoretically saturating the categories (Holton, 2010). Thus, we concluded by employing an abductive approach to connect interview information to concepts such as alignment work and linguistic resources (Timmermans and Tavory, 2012). Ultimately, we compared accounts of knowledge practices, tensions, challenges, and expressed benefits, seeking similarities and differences across the three projects, guided by the previously described theories and concepts. Moreover, the fieldwork notes were crucial for identifying compelling issues to explore in the interviews from projects A and B, as well as for interpreting interview statements.

We predominantly used interview quotes to present the outcomes of the analysis, as they provide the most concise information. However, the fieldwork notes were employed to describe the laboratory activities in projects A and B. We examined the publication data primarily to map the presence of interdisciplinary and disciplinary publications. We characterise publications as interdisciplinary when the authors come from two or more disciplines.

We promised the interviewees anonymity. To manage confidentiality concerns arising from the small size of the community we study, we chose not to disclose the gender and position of the interviewees when quoting them, merely distinguishing between early-career (PhDs and postdocs) and senior researchers. This restriction also means that we cannot reference the analysed articles.

We commence the presentation of findings by analysing the moral economy of interdisciplinarity across the three projects as contexts for the integration processes. In the subsequent step, we explore each project, examining how the interviewed scientists described the integration processes, emphasising the exchanges of materials, data, and calculations, including the alignment work and calibration efforts. We then analyse the scientists' accounts of their experiences concerning the skills required for the interdisciplinary work in which they were engaged and how they acquired these skills, which were primarily related to articulation work.

The moral economies of the epistemic machineries of interdisciplinarity

Analysing the moral economies of interdisciplinarity involves studying how scientists understand and value the concept, as well as assessing whether their perspectives create a system of meanings that may influence integration practices. Regarding the three projects, we examined how the interviewees articulated their interdisciplinary collaboration, along with its aims and benefits. We found widespread agreement within each project on these matters, including affective engagement, indicating the presence of a moral economy of interdisciplinarity. What were the main features? We begin with Project A.

The scientists involved in Project A observed that their disciplinary backgrounds were diverse, while recognising the importance of incorporating such a heterogeneous set of competencies to achieve the project's scientific goal. Furthermore, they understood interdisciplinarity as a collective endeavour, driven by the participants' acknowledged interdependence in reaching the common aims. For example, one senior scientist explained that s/he saw the planned organisation of the project as central to the meaning and conduct of interdisciplinarity. S/he argued further that, in general, scientists ought to be better at planning integration at the idea stage and should be more specific in describing their interdisciplinary collaboration practice. They should go beyond stating why they would include the scientific groups to outline how and to what end they would collaborate. The grant application for Project A provided such information, which emphasised a relay structure.

When asked about their interdisciplinary collaboration, the scientists in Project B identified three main participating groups: biologists, bioinformaticians, and mathematicians. The biologists were considered dominant. They usually led meetings, made decisions regarding further project actions, and conferred with the PIs from bioinformatics and mathematics. Scientists in the three groups perceived themselves as having distinct disciplinary competencies and methods, even if there were specialities within the groups. However, to all interviewees in Project B, interdisciplinarity meant acknowledging that collaboration across disciplines was necessary and that the competence of all groups in the project was needed. This collaborative spirit characterised the moral economy.

The scientists from Project C described themselves as theorists or experimentalists, distinguished by different experiences, skills, and perspectives. The project manager repeatedly emphasised, "You have to talk to some experimentalists, not only physicists and mathematicians, to get the different experiences." When asked to describe their daily interactions and collaboration with others, all scientists explained that the research centre was interdisciplinary, even if many said that they did not collaborate that much in their daily work. An early-career scientist in Project C, for example, commented:

> I work very little with experimental data and stuff. So, it's not so much [collaboration]; I don't talk to the experimentalists as much as I ideally should. But it can be a little tricky to know what to talk about. Or [it] can be a bit like 'sitting with one's stuff' (early career researcher, project C).

Some explained that their research plans did not require much interaction with others, or as articulated by another early-career researcher in project C: "Mostly, [I do] independent work." Thus, working in an interdisciplinary centre did not necessitate interaction across disciplines. One of the senior scientists explained:

> What I am saying is that they [the scientists in the research centre] retain their discipline, so even though they work in a highly interdisciplinary environment, not everyone here works in an interdisciplinary way.

Nevertheless, the same scientist emphasised that having project participants from complementary fields, particularly biology and mathematics/physics, was crucial for achieving scientific breakthroughs within brain research.

Overall, the interviewees characterised the project as a blend of disciplinary and interdisciplinary practices. Interdisciplinarity primarily referred to some form of collaboration across disciplines, which was essential for the project to achieve its goals. However, only some individuals had to cooperate. This situation afforded the participants in Project C an interdisciplinary identity at the group level, despite the varying degrees of interdisciplinary engagement among the individuals.

To summarise, we observed two distinct moral economies of interdisciplinarity. The interviewees in Projects A and B described a moral economy in which interdisciplinarity was mandatory but also engaging. Such collaboration was essential to achieving a shared goal. Although their research was discipline-based, the scientists also identified as interdisciplinary researchers, since everyone was expected to participate in the exchange of materials and knowledge across disciplines, and they did so with a measure of enthusiasm. In contrast, the interviewees from Project C noted that interdisciplinary exchanges could be fruitful, but participation in them was not required, and they had long debated the project's goals. They described a more complex and less affective moral economy where interdisciplinarity was optional, although some scientists felt compelled or wanted to engage. Nevertheless, they expressed an interdisciplinary identity, primarily at the group level. Moreover, in all projects, there was widespread acknowledgement of disciplinary differences – cognitive contextualisation (Lamont, 2009).

Regardless of whether the moral economies indicated that interdisciplinarity was mandatory or optional, disciplinary practices still prevailed. This was also evident from the publications, which comprised a mix of disciplinary and interdisciplinary contributions across all three projects. This finding suggests that the differences in the moral economies only modestly influenced their epistemic machineries of interdisciplinarity. Did all three projects engage in relays in the same way?

Project A: The epistemic machinery of a singular relay for integration

In the theory section, we identified three main features of the relay model to explore in the empirical analysis of the projects' integration practices: the conduct of alignment work, which included infrastructuring through socio-material facilitators, articulation work (interdisciplinary communication), as well as calibration efforts. However, we begin by examining the project structure and fundamental activities to assess the primary features of the relay.

Project A consisted of six work packages. As previously noted, it was designed as an interdisciplinary, multi-step supply of materials, data, and calculations from one work package to the next. Thus, the project was organised as a single relay. When the relay model was presented at a poster session in 2019, a senior researcher from Project A exclaimed: "Relay! Yes, that's exactly what we are doing!".

The project plan required the work packages to commence sequentially in a relay manner, ensuring that when outcomes from one work package became available, the next in line would initiate. Therefore, a crucial aspect of the project's integration efforts was its organisation as a series of temporally ordered work packages – laps – each with a specific research focus. Furthermore, the epistemic machinery of Project A necessitated exchanges between the laps, wherein biological material, data, and knowledge were conveyed. What methods did the relay organisation provide to facilitate this traffic? What alignment work took place?

A group of biotechnology scientists initiated the project. Their task was to create three-dimensional alginate gels in which the cells under investigation could thrive. The scientists experimented with various concentrations of substances and applied pressure to the gels to fulfil the requirements for facilitating three-dimensional growth. Shortly after the first group's efforts commenced, another team from a partner organisation began working with the provided gels. They aimed to grow the targeted cells within these gels, but struggled to ensure they survived.

Creating a suitable gel proved difficult. The two groups had to calibrate their efforts to achieve this aim. They engaged in diverse exchanges of materials, including fluid solutions, cells, information on buffer concentration, images, tables, and graphs. The scientists managing cell growth relied on the work of the alginate group, and vice versa. Data were communicated via email and meetings, while biological materials, such as alginate and cell lines, were delivered in person. Thus, the transfers were socio-material, involving human interactions and technological infrastructure. In this way, the scientists carried out alignment and articulation work.

The next stage involved extracting RNA from the cells for screening and then transferring the data to bioinformaticians for analysis to develop the envisioned computational model. Challenges with cell viability led to a delay, but the bioinformaticians eventually received the data they needed to fulfil their role in the project. Accordingly, when the interviewees found the exchanges between the work packages difficult, it was primarily – but not exclusively – due to the need to synchronise them.

Overall, the scientists in Project A characterised their interdisciplinary integration efforts primarily as the organisational achievement of arranging the work packages into a single relay, thereby providing a framework for the necessary alignment work. A senior researcher outlined the resultant interdependencies that had to be managed:

> [E]veryone is dependent on each other in the process. So [a bioinformatician] needs data from [project partner D] (…) to be able to work. [Project partner D] must have material from us (senior researcher).

The alignment work was performed through the laboratories' socio-material infrastructure, which included measuring devices, computers, and the Internet. Occasionally, materials, data, and calculations needed to be transferred between the work packages due to the necessity of calibration. Furthermore, the relay practice required effective communication across the participating disciplines, specifically, articulation work. Ensuring that the conveyed materials and data were fully understood was deemed challenging. Several interviewees emphasised that physical meetings were crucial for clarifying information and providing assistance when calibration was necessary.

The project manager contributed to the articulation work by providing a list that explained key concepts and terms. This contribution also facilitated calibration and the development of cognitive contextualisation – the awareness and consideration of disciplinary differences among the scientists in the project. Furthermore, many interviewees praised the project manager's ability to act as a broker, thus assisting with the articulation work to communicate effectively across disciplines. At the same time, several emphasised that they only needed to understand certain aspects of the project. This practice was grounded in trust. A senior scientist explained that in project A:

> which is a big project, you've got those core competencies that you can trust. And, ok, when [bioinformatician A] says that he needs five nanograms, one hundred nanograms RNA, I can trust that (…). So, it's very okay to just say, 'Ok, I know that s/he knows what s/he is talking about.' (…). Sometimes I've thought, I don't need to check and read myself up on this issue because somebody else knows.

The quote highlights the significance of trust as part of the moral economy of interdisciplinarity that facilitated aligning the work packages and the performance of articulation work. The senior scientist elaborated:

> In [project A], we talk very well together. And no one cares very much about presenting very complex stuff. So, you try to do your best to explain things to somebody who doesn't know them instead of talking as advanced and complicated as possible.

Trust may also diminish the need to develop interactional expertise as a skill for articulation work. Commenting on the communication between biologists and bioinformaticians, another senior scientist explained

> When [biologist B] talks about genetics … I have worked a lot with proteomics, which is quite close, but at the same time, so are genes and proteins different, and they are talked about in quite different ways (…). I could have spent much time understanding [how to do genetics and genomics], and then I think I don't really need that because they [the bioinformaticians] are there.

Thus, in Project A, interdisciplinarity was shaped as a stepwise integration process of the outcomes from the sequentially organised work packages, functioning as a single relay for transferring the outputs facilitated by alignment work. This relay formed the basis of the project's epistemic machinery. The pragmatic efforts of the project manager to support the necessary articulation work were significant. The interviewees acknowledged communication challenges; yet, in keeping with the project's moral economy, they were motivated to find solutions. Furthermore, it is noteworthy how trust among the scientists considerably reduced the need for articulation work.

We previously learned that Projects A and B's moral economies of interdisciplinarity were similar. Did that imply that the central features of the projects' epistemic machineries were also alike?

Project B: The epistemic machinery of multiple relays

Project B's epistemic machinery of interdisciplinarity was also based on the relay model, though not in the same linear manner as in Project A. Instead, there were three relays. The interviewees described the primary relay as a two-step exchange process. Firstly, data from the biologists' experiments were transferred to the bioinformaticians for analysis. Secondly, the bioinformaticians handed their results to the mathematicians for model building. Occasionally, the biologists provided data directly to the mathematicians, constituting the second relay. After the bioinformaticians and mathematicians had analysed the data, they often wished to return the results to the biologists. This reverse step formed the third relay.

There was no exchange of biological material. The scientists only exchanged information, primarily the measurements obtained by the biologists and the results of calculations and modelling. The biologists conducted experiments with cod, such as exposing liver slices to various toxins and measuring the effects. They recorded the measurements in Excel sheets that they shared with the bioinformaticians and mathematicians.

These sheets were a vital socio-material infrastructure in Project B, serving to align the efforts.

For example, when the interviewed biologists analysed the genes of cod exposed to varied environments, they endeavoured to measure whether genetic differences related to these different exposures. Subsequently, the biologists often performed what they referred to as "the simple analysis" (early-career researcher). However, when they wished to conduct "all the different tests from the same fish" (early-career researcher), they consulted the bioinformaticians and mathematicians, transferring information to them because they knew how to perform such comprehensive analyses. According to one of the early-career researchers:

> At least for my part, when we have involved bioinformaticians or mathematicians, I want all the different tests from the same fish, right, because they can run more extensive analyses … then you can do a variety of biological data, both at the protein level and the gene level and perhaps the weight of the fish and so on, to see whether it has been affected by the exposure and similar things … so that you can see 'Ok, it is the exposures that make these differences visible'.

In this manner, the scientists engaged in calibration to overcome frictions in the exchanges. A bioinformatician explained that s/he regarded it as his/her job to upload the bioinformaticians' analyses to the project's data-sharing platform – the Excel sheets – so that the mathematicians could collect whatever data they needed from the platform without further communication. They struggled to succeed with this alignment work, partly because some articulation work was also necessary. One mathematician provided an example. S/he had spent a lot of time and effort finding the required data and needed to consult Wikipedia to understand the underlying biological concepts. Perhaps the biologists should have put in more articulation efforts. One concept that the biologists used, and took for granted that the mathematicians understood was 'omics', which informally denotes a field of study ending in '-omics', such as genomics.

To avoid misunderstandings and improve the scientists' cognitive contextualisation, Project B conducted annual workshops where they, among other things, learned and explained core disciplinary concepts to one another. They engaged in this articulation work with a twist: the scientists were not allowed to explain 'their own' concepts but had to choose terms and concepts from other disciplines within the project. The scientists described these workshops as highly valuable:

> Before this workshop, I, you know, like I asked people, ok, what is proteomic? What is transcriptomic? Because they were talking about this stuff … and then they tried to explain it, but I couldn't really get it. (Early-career researcher, mathematician)

We see this as an effort to develop interactional expertise that could facilitate the exchanges.

The communication challenges in Project B seemed most significant between the biologists and the mathematicians. "Having different languages" was a frequently used expression. This situation was considered a barrier to the development of the epistemic interdependence that would foster integration across disciplines:

> So, well, we each have our language … if you know the language, then you know the discipline. And I think much that they [biologists] talk about is not like … it won't be logically tricky for me to understand, but I don't know the language, and that's why I don't follow, right? While math is perhaps a bit different.(Early-career mathematician)

Thus, the scientists needed to develop articulation work strategies that acknowledged what they called linguistic differences. The mathematicians expressed this need most clearly, emphasising that they had to avoid using numbers when communicating results to biologists:

> I think graphs are more descriptive and probably more understandable for them, so I prefer to communicate with them using graphs and stuff like this instead of numbers. (Early-career scientist)

Another mathematician had learnt that when talking with biologists,

> I should explain it in words. Like, say, [I should explain the] interpretation of the result, and then they understand what I mean.

Bioinformaticians were observed to facilitate the exchanges of data and calculations by attempting to "bridge the biologists and the mathematicians," as one bioinformatician described it. Their dual competence meant they shared some linguistic skills with both the biologists and the mathematicians. Consequently, they had two-way interactional expertise.

However, the interviewed scientists explained that alignment could be challenging as they might interpret data differently, necessitating calibration. The biologists could not simply send their measurements and say, "Do something with this" (early-career researcher). They had to specify the kind of data they had collected and what they wanted the other groups to do with it. Yet, biologists often believed that bioinformaticians and mathematicians were able to "just do something" or "run some analysis" (early-career researcher) with the data and derive something interesting. Nevertheless, the planned relays of exchanging data and calculations between the disciplinary groups of scientists shaped the integration efforts in Project B.

The fundamental structure of the relay model remained consistent in Projects A and B, featuring organised sequences for transferring materials, data, calculations, and knowledge. The groups of scientists conducted their research in accordance with their discipline-based practices. The relays reflected the projects' directionality, which propelled the integration of the discipline-based contributions. Critical moments arose during the exchanges, necessitating alignment and articulation work that was executed somewhat differently in the two projects, partly due to differing socio-material infrastructures. In Project B, the bioinformaticians served as a resource for articulation work, as they possessed dual interactional expertise in biology and mathematics. How was interdisciplinary work organised in Project C, where the moral economy permitted such work to be optional?

Project C: Optional circular relays

Project C also had a work package structure, but without predefined exchanges. Most of its scientists worked in the same hallway and considered this co-location essential for fostering collaboration. Furthermore, the project was part of an interdisciplinary centre, and interdisciplinarity was given special consideration on the project website, which stated,

> Extra measures are in place to bridge the different disciplines. These include co-localisation, sharing office space, and working together to create a common vocabulary and more thorough understanding of each other's disciplines.

Therefore, articulation work was highlighted, but there was no mention of the directionality of the work packages as a driver of integration.

Thus, interdisciplinary integration in Project C depended on the scientists recognising the necessity of collaborating across disciplines or specialities. Such recognition could encourage exchanges between experimentalists and theorists. One neuroscientist explained how s/he began working with a computational mathematician when s/he needed such collaboration to derive more from her data.

> For example, [name of computational mathematician] was not in my work package, but at some point, the data I was getting were like, 'Oh, maybe [the computational mathematician] can bring in modelling expertise,' and then add some richness to the data that we are getting. (…) And I've seen that, gradually, people [in the project] are beginning to find that 'oh, but I think that such expertise might be really useful'.

This account was typical. Integration across disciplines was not required, reflecting the lenient moral economy of interdisciplinarity. However, when such collaboration was viewed as appealing, experimentalists and theoreticians would exchange data and results through a circular relay. The former supplied data, while the latter provided output from modelling or calculations. The scientists' accounts suggested that many, through such practices, developed cognitive contextualisation and recognised their epistemic interdependence. This development was also evident in how they acknowledged the limits of their expertise as a motivation for collaboration.

> We are not embarrassed by not knowing things. Therefore, [name of senior researcher] cannot do what I can, and vice versa. That's perfectly acceptable. In a way, senior individuals must be brave enough to admit that they don't understand what some PhD candidates discuss. (Senior scientist)

One of the senior scientists explained how they depended on each other's willingness to work interdisciplinary towards the same goal and the significant role of seniors:

> Yes, it's clear that without seniors trying to get this [interdisciplinarity] working, it will stop [laughed]. And seniors who are not too inflexible either.

Communication challenges were prevalent in the accounts. Participants required interactional expertise or other forms of articulation work to exchange data or calculations across disciplines effectively. Most of those involved in Project C concurred that communication in this context required an understanding of aspects of the other discipline and observed that they had not acquired this knowledge through formal education. A senior researcher explained that some scientists could act as bridges. "Those who can do both [experiments and theoretical work] are worth gold." Such expertise enabled those scientists to understand the various parts of the project better. They could also elucidate the differences between theorists' and experimentalists' daily work. However, most interviewees felt a need to develop at least some interactional expertise.

> I learn more and more about biology, so I understand what people are talking about increasingly better, but there is still so much I don't know. And there is a lot they don't know about what I can, and it is difficult … at least when presenting to the whole group, coming across so that everyone understands. (Early-career scientist)

The interviewee continued to explain a limitation of interdisciplinary communication that s/he considered significant. "[Y]ou also want to get to where you can have a little more in-depth discussion. But you don't get that if you just talk about the simple things." Sometimes, s/he argued, they needed to address issues in more specialised exchanges, which was easier to do with people from the same discipline. Accordingly, many interviewees emphasised disciplinary work more explicitly than the scientists involved in the other two projects.

Conclusion: The relay model comprising socio-material integration practices

This article presents the relay model as an epistemic machinery of interdisciplinarity that highlights socio-material features of integrating epistemic activities across disciplines when the project is organised as a directional set of exchanges. Existing research into interdisciplinarity tends to emphasise cognitive integration strategies, such as modelling. However, studies like Nersessian (2019) demonstrate that interdisciplinary projects may involve directional exchanges of materials, measurements, calculations, and knowledge among discipline-based researchers. Such observations suggested to us that the relay model introduced in the article's theory section might serve as a fruitful starting point for examining projects that are infrastructuring such exchanges, for instance, through a work package organisation. Therefore, we wished to investigate the alignment and articulation work involved in achieving the exchanges. Furthermore, we aimed to explore the engagement in tackling interdisciplinary challenges by studying the projects' moral economies of interdisciplinarity and their significance. We found that this engagement went deeper than just catering to instrumental needs for collaboration. It resulted in the development of identity as interdisciplinary scientists and trust across disciplines.

We found the relay model to be a fruitful representation of the interdisciplinary integration practices of the three projects we studied. Infrastructuring occurred through the organisation of the projects, the use of software, the internet, and computers for exchanges, as well as regular physical meetings and workshops. These tools facilitated alignment work alongside the projects' distinct moral economies of interdisciplinarity, which encouraged cognitive contextualisation by recognising disciplinary differences and the need for articulation work. In addition, some calibration efforts were necessary to achieve common standards and interpretation. The articulation work was sometimes aided by available interactional expertise, such as that of bioinformaticians. Still, in most cases, it required effort to grasp basic concepts from other disciplines or to use communication tools such as figures or verbal simplification. Trust appeared to reduce the need for articulation work. However, we found no evidence of interlanguage development, likely due to the short time frame of the projects.

As noted in the review of existing research on interdisciplinarity, integration efforts are often described as modelling, product design, scenario-building, and cost-benefit analysis. The involvement of social scientists or humanities scholars can enhance integration by introducing new perspectives or advocating for reflective efforts concerning ethics and issues related to the research's social responsibility (Fisher et al., 2015; Smolka, 2020). However, it is less clear whether such reflections are integrated into the knowledge produced by these projects. Perhaps the main effect is to influence the direction of the research efforts to ensure that they are socially responsible, for instance, by the use of toxic (Åm and Sørensen, 2015).

The primary advantage of the relay model is that it provides a broader perspective on integration practices, extending beyond the amalgamation of knowledge from various disciplines. In this model, integration is understood as a socio-material endeavour involving exchanges between the discipline-based production of materials for examination, measurement, calculation, and modelling that may be parts of interdisciplinary research. As we have shown, these exchanges may be facilitated by diverse infrastructuring and articulation work. Thus, the relay model represents the underlying epistemic machinery of a project's practice of interdisciplinarity. Furthermore, we believe that the model promotes explicit reflection on integration methods. However, the relay metaphor's origin in sports may suggest that speed and competition are vital in interdisciplinary research. This interpretation is partly correct, since there is pressure to keep deadlines, and science is often competitive. However, the main motivation for using the relay metaphor was our focus on the conduct of exchanges, which we see as a vital feature of the integration efforts undertaken by the analysed projects.

Kruse and Silvast (2023) suggest that it might be more appropriate to describe the movement of knowledge between distinct epistemic cultures as multidisciplinary instead of interdisciplinary. They argue that the alignment work undertaken to bridge the 'seams' between the disciplines leaves their epistemic cultures unchanged. We disagree. Our study demonstrates that alignment efforts, and particularly the necessary articulation work, represent modifications of the discipline-based cultures. While disciplinary identities were reproduced, interdisciplinary communication skills and identities emerged; the latter were expressed in the observed moral economies of interdisciplinarity.

Alignment work may be a concept that enhances the utility of Knorr Cetina's (1999) ideas about epistemic cultures for studying the movement of knowledge (Kruse and Silvast, 2023). The relay model contributes to this by demonstrating how appropriate epistemic machineries can facilitate interdisciplinary research. Although alignment is critical, it is insufficient. Adequate infrastructuring, reciprocal articulation work among scientists, and calibration efforts are essential to ensure successful exchanges between the discipline-based work packages.

We suggested in the introductory outline of the relay model that it may serve as a generative approach to configure interdisciplinary efforts in contexts characterised by a series of exchanges of material, data, and calculations. The outcomes may be diverse, and implementing the model may require creativity. It cannot depend on infrastructuring to stabilise exchanges, as Kruse (2021) describes. Research requires flexibility, which can be achieved through articulation work, calibration, and trust. Typically, many interviewees explained that they viewed the performance of exchanges across disciplines as an ongoing learning process. Moreover, some scientists stated that they regarded much of what they learnt in the projects as specific and only temporarily useful. Whether the skills acquired would apply to their next project remained unclear. Indeed, some expressed sadness that all the expertise in performing interdisciplinarity they had developed "now just disappears when the project ends" (early-career scientist). This dynamism should be recognised as a core aspect of the relay model. It appears that the model requires reinvention regarding the involved activities. Further research is needed to examine this assumption. Participation in a series of relay-based projects may lead to the accumulation of skills that facilitate future relay practices.

This article has focused on biotechnological research, where the relay model appears to be an appropriate analytical tool for identifying integration practices. Additional research is needed to examine the applicability of the model for analysing integration in interdisciplinary research across other subject areas and differently organised projects. It may be less suited to study integration between STEM research and humanities and social science scholarship, but that should be investigated. Still, we want to emphasise that the relay model can serve as a tool for both funders and practitioners of interdisciplinarity to rethink how the integration of data and knowledge may be performed in comprehensive interdisciplinarity contexts.

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