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Abstract

In this paper we contribute to a processual understanding of knowledge integration in interdisciplinary collaboration by foregrounding the role of dialogue in dealing with epistemic uncertainty. Drawing on an ethnographic study of collaboration among scientists involved in developing a highly novel bioreactor, we suggest that knowledge integration is not a homogeneous process, but requires switching between different knowledge integration practices over time. This is particularly notable in the case of 'epistemic breakdowns' - deeply unsettling events where hitherto held understandings of the nature of problems appear unworkable. In such cases, it is not sufficient to deal solely with coordination issues; collaborators need to find ways to address generative knowledge integration processes and to venture, collectively, into the unknown. We demonstrate how this generative quest of knowledge integration is achieved through a dialogical process of drawing and testing new distinctions that allows actors to gradually handle the epistemic uncertainty they face.

Keywords: Knowledge integration, dialogue, interdisciplinary collaboration, process studies, epistemic uncertainty, breakdown

Introduction

> For over a year now the team of scientists has been working together on a project to develop a bioreactor for the controlled growth of stem cells; a project that has never before been attempted. They had defined the precise parameters towards which to work and each group of specialists had been given clear deliverables. After having brought together the various parts of the bioreactor and conducted the first experiments, they now face an inexplicable situation. The results are entirely unexpected. Moreover, scientists do not know how to read them, nor do they have a clue as to the underlying reasons. The senior bioengineer bluntly declares his ignorance: 'What is happening here?' No one knows the answer. And what is worse, no one knows what the problem is. Earlier in the project, scientists had met various situations when things did not work according to plan, yet this time is entirely different. The Principal Investigator is clearly agitated and later comments that it feels as if they have landed on an unexplored planet where their usual ways of explaining, or even approaching, a problem do not seem to hold. In fact, it took them 6-months to find a way to tackle the issue.
>
> (From field notes)

Innovation journeys in novel territory can sometimes encounter situations like the one described above. An interdisciplinary group of specialists meets an unanticipated and entirely inexplicable situation, in which their expertise does not allow them to grasp what the problem is, let alone how to resolve it. They do not know how to go on. In this paper, we will focus on such situations, which we come to call 'epistemic breakdowns' - deeply unsettling events, both cognitively and emotionally, where hitherto-held understandings of the nature of problems appear unworkable. By analysing the dialogic work that goes into coping with such breakdowns, we develop a processual account that helps to explain how knowledge is integrated in the face of epistemic uncertainty.

Knowledge integration is a central concern in organization and innovation studies. The development of new knowledge often arises at 'the interstices' of disciplines with diverse specialised ways of knowing and doing (e.g. Pavitt, 2005, Carlile, 2004). Understanding knowledge integration - that is, the process through which specialised knowledge is drawn together and combined to create new knowledge (Okhuysen and Eisenhardt, 2002: 371) - is therefore crucial.

Knowledge integration is seen as especially important when underlying science and technologies are radically new or untested (Tuertscher et al., 2014). Situations where the relevant parameters of a phenomenon are unknown, casual relations become unclear and interdependencies among parties become unpredictable, generate 'epistemic uncertainty' (Grandori, 2010, Dougherty and Dunne, 2012). The terms refers to the fact that in such conditions what counts as knowledge becomes an open question (Dougherty and Dunne, 2012, Dunne and Dougherty, 2016). In the face of epistemic uncertainty knowledge integration becomes extremely challenging, not least because other more established means of coordination, such as conforming to a predefined plan or system architecture, are largely precluded (Tuertscher et al., 2014). Collaborators not only have to tackle the challenge of coordinating their existing knowledge (Tell, 2011, Tuertscher et al., 2014) but also need to find ways to collectively venture into the unknown. Yet, the issue of how knowledge integration is accomplished in conditions of epistemic uncertainty remains largely unexplored (Dunne and Dougherty, 2016, see also: Tuertscher et al., 2014). Accordingly, in this paper we aim to respond to the following question: how do specialists from diverse disciplines integrate knowledge when they are faced with epistemic uncertainty?

We address this question by focusing on an aspect rarely addressed in the literature, namely how knowledge integration is achieved through dialogue. We understand dialogue as the 'joint activity between at least two speech partners, in which a turn-taking sequence of verbal messages is changed between them, aiming to fulfil a collective goal'[1] (Tsoukas, 2009: 943). The limited attention to dialogue in relation to knowledge integration is surprising given its importance in interdisciplinary work (Faraj and Xiao, 2006, Marcos and Denyer, 2012, Majchrzak et al., 2012) and when learning in novel situations (Bosma et al., 2016, Schein, 1995). Accordingly, our secondary aim is to explore what kind of dialogic work supports knowledge integration in situations characterized by epistemic uncertainty.

[1] This definition of dialogue is much narrower than important theorists of dialogue have proposed, such as Mikhail Bakhtin who suggested that cultural expressions of any kind are dialogic in nature as they presuppose earlier statements and anticipate future responses (cp. Cunliffe, 2002).

To address our two aims, we build upon a processual approach and the idea that organizational processes do not entail steady or linear flows and instead unfold in a dynamic, stepwise and iterative manner (Segal, 2017, Langley et al., 2013). This invites a focus on critical events and how these are related in time (Tsoukas, 2009). Drawing from an ethnographic study of collaboration among scientists developing a wholly untested form of bioreactor for the growth of stem cells, we show how the micro-interactional practices of knowledge integration shift when collaboration partners face what we call an 'epistemic breakdown'. Specifically, scientists change their mode of knowledge integration from tackling the problem of coordination, which allows them to translate knowledge across disciplines, to a generative process of re-drawing distinctions. Only by drawing new distinctions in dialogue can the interdisciplinary group of specialists reach forward towards the yet unknown and gradually overcome the epistemic breakdown.

Knowledge integration under conditions of epistemic uncertainty

Interdependence within a specialised division of labour creates a fundamental tension in organizational processes. Specialised practice generates boundaries across epistemic communities, which pose significant challenges to the coordination of work (Kotha et al., 2013). While there is little value in specialists acquiring in-depth knowledge of their collaborators' specialisms - this would demand costly efforts of mutual learning

(Eisenhardt and Santos, 2000, Majchrzak et al., 2012, Schmickl and Kieser, 2008) - specialists do need to have some common ground to be able to work together (Carlile, 2002). Thus, rather than a 'deep' sharing, knowledge integration may involve simply mentioning and displaying knowledge (Majchrzak et al., 2012, Schmickl and Kieser, 2008).

This need to balance differences and common ground led most previous work on knowledge integration to focus on the so-called 'coordination problem': how to translate and transform knowledge across the boundaries of specialist groups (Tell, 2011). For example, studying the development of a new particle detector system, Tuertscher et al. (2014) found that a 'boundary infrastructure' comprised of texts, tools and simulation models enabled 'tacit coordination'. This allowed scientists to anticipate and make sense of each other's actions. Knowledge can also be integrated by engaging in practices in which knowledge is simply voiced and displayed, rather than fundamentally transformed (Majchrzak et al., 2012, Schmickl and Kieser, 2008). Other authors focussed on the 'co-operation problem' (Tell, 2011) that is, how to align interests and identities of interdependent actors (Kellog et al., 2006) so that they are willing to engage in knowledge integration. In innovation situations, where knowledge is 'at stake' or up for debate (Carlile, 2004), actors may be particularly sensitive to the political and pragmatic consequences that could arise from the disruption of existing routines (Deken et al., 2016) and from the questioning of jurisdictions of knowledge and work (Mørk et al., 2010).

Such explanations of knowledge integration apply well in situations where problem parameters are reasonably well understood and/or where dependencies among specialists, and the contributions they bring, are relatively well defined (e.g. Majchrzak et al., 2012). In contrast, in situations of epistemic uncertainty, for example, when developing a new system or drug based on an uncertain technology and science (Tuertscher et al., 2014, Dunne and Dougherty, 2016), addressing only the coordination/cooperation issues in knowledge integration may not be enough. In these situations, the parameters of the problem and the interdependencies among specialist forms of knowledge that may lead to 'its' resolution (whatever 'it' is), still need to be worked out (Swan et al., 2015). This 'working out' and expanding of collective knowledge in order to venture into the unknown requires a generative process of knowledge integration, which to date remains still poorly understood (Tuertscher et al., 2014, Salazar et al., 2012).

The kind of generative effort needed when integrating knowledge in the presence of epistemic uncertainty can be better understood by turning to studies that have explored novelty and complexity in innovation (Carlile, 2004, Majchrzak et al., 2012, Bruns, 2013, Deken et al., 2016). For example, authors argue that when novelty is such that causeeffect relations among elements are largely unknown, problems cannot be solved by 'weeding out' already known alternatives (Dougherty and Dunne, 2012, Swan et al., 2015). Actors need to work the other way around, seeking to 'reach forward from known starting conditions (theory) to search for unknown outcomes; by weeding in, not out, and by opening up to general questions rather than pulling in to particular answers' (Dougherty, 2007: 266). A similar point have been noted by Knorr Cetina (2008), who showed that scientists in novel contexts proceed by 'branching out' (p.92). Practitioners have to sustain the collaboration while the goals remain fuzzy. They need to collaboratively reach out to a moving target that remains partly unknown. In this paper we argue that 'branching' or 'reaching out' to unknown outcomes and 'weeding in' alternatives relies centrally on dialogical interactions among collaborators.

The role of dialogue in the knowledge integration: Towards a processual account

The important role of dialogue in organizational knowledge, learning and reflexivity has been widely acknowledged in the literature (von Krogh et al., 2000, Tsoukas, 2009, Senge, 1990, Schein, 1995, Mazutis and Slawinski, 2008, Cunliffe, 2002). For example, dialogue has been found to be key to organizational learning as it allows practitioners to engage in a reflexive practice connecting tacit knowing with explicit knowledge (Cunliffe, 2002). Nonaka and Konno (1998) suggested that dialogue is central to the development of new concepts and the externalization of tacit knowledge (Mengis and Eppler, 2008, von Krogh et al., 2000).

Despite dialogue's noted centrality, empirical analyses on dialogic practices and their relationship to learning and innovation remain limited. More specifically, we have a limited empirical understanding of dialogic practices when integrating knowledge. When novelty and uncertainty rise, dialogue may become important, especially for the generative process of knowledge integration (Majchrzak et al., 2012, Faraj and Xiao, 2006). Dialogue allows collaborators to take a distance from habitual interpretations and create new distinctions (Tsoukas, 2009). Through dialogue, distinctions can be drawn within a collective domain of action and practitioners may engage in a reflexive activity of 're-ordering' and 're-arranging' their understandings of the world (Tsoukas, 2008: 953). For Tsoukas (2009), dialogical practices enable knowledge creation by allowing 'ever-finer distinctions' to be made, such that 'what was hitherto thought of as a unitary phenomenon becomes split into parts' (Tsoukas, 2009: 942). This reflective practice is often triggered by interruptions to the daily practice (Weick and Putnam, 2006) and requires a productive dialogue in which 'interlocutors attempt to assimilate mutually experienced strangeness, and by doing so, they are stimulated to draw new distinctions' and thus to expand knowledge collectively (Tsoukas, 2008: 169). Exploring how distinction-making unfolds in and through dialogue is thus critical to understanding how knowledge integration unfolds in situations of epistemic uncertainty.

Understanding the role of dialogue in knowledge integration, in turn, requires conceiving the latter as a process rather than an outcome (e.g. Okhuysen and Eisenhardt, 2002). By approaching knowledge integration as an ‘evolving phenomena’ (Langley et al., 2013: 1), we are sensitised to the possibility that the process may change over time. Bruns (2013), for example, found that coordination across a group of scientists alternated between working relatively alone (coordinating through alignment and interface management) and occasionally collaborating more closely (coordinating through joint assessment and consultation). Faraj and Xiao (2006) found, similarly, that coordination practices in a trauma centre changed when an unexpected event interrupted habitual trajectories as the clinical team started to rely more on ‘dialogic coordination’ involving protocol breaking or joint sense making. In order to better understand what explains such dynamics in knowledge integration, a focus on breakdowns and interdependences between practices is useful. It has already been shown that interdependences can contribute both to the stabilization of practices and the emergence of new ones (Deken et al., 2016). At the same time breakdowns, defined as ‘disruptions of the normal, taken-for-granted flow of practice when things don’t go as expected’ (Lok and De Rond, 2013: 186), may offer particularly favourable junctures to study dynamics of knowledge integration and its generative quality. This is because breakdowns represent situations when novelty (Deken et al., 2016) and epistemic uncertainty are intensely experienced and collaborators are exposed to unknown possibilities (Holt and Cornelissen, 2014).

In sum, a number of studies corroborate the idea that: knowledge integration may not be a homogenous process; we could gain insights on the dynamics of the process by focusing on breakdowns; and that dialogue may play a particular role when faced with situations of epistemic uncertainty. In the rest of the paper we shed further light on the phenomenon building on the results of our case study.

Research Site and Methods

We build our theoretical insights from a focused ethnography (Knoblauch, 2005) of an interdisciplinary group of scientists trying to develop an entirely novel type of bioreactor for controlled stem cell growth at a major university in the United Kingdom. We entered the field with a relatively broad aim in mind, namely to further the understanding of interdisciplinary collaboration. Given our background in practice and process theories, we decided to work with a focused ethnography as our main method of inquiry since it allows for the development of context specific understandings of day-to-day activities and interactions over time (Nicolini, 2012, Pink, 2009, Langley et al., 2013). Focused ethnography refers to studies focused on a specific area of inquiry and is characterized by a small-scale focus, shorter field visits, more data and analysis intensity, and a greater focus on communicative activities in comparison to classical ethnography (Knoblauch, 2005).

Data collection

In line with the ethnographic tradition, data collection involved a combination of non-participant observation, qualitative interviews and documentary sources (Yanow and Schartz-Shea, 2006). During 8 months, we conducted selected observations of the work and interaction of the scientists (120 hours in total), with the second author attending most of the periodic scientific project meetings (9 in total), and taking part in other formal and informal events and gatherings, such as lunches, impromptu meetings and seminars. Observations were also conducted in each of the laboratories involved. Observations were coupled with in-situ ethnographic interviews (Spradley, 1979) and semi-structured interviews (23 in total) carried out over a longer, 18-month period. In particular, we interviewed 11 of the 18 scientists most involved in the project at two different points in time, thus generating sequences of two (and occasionally three) interviews per scientist. All interviews, and five of the monthly meetings, were transcribed verbatim. Finally, we collected the documents and the scientific papers produced during the project, which included various versions of the project proposal, the project report, and the PowerPoint slides used during presentations.

Analytical techniques

The interpretation of data started during data collection through the writing of memos and the ongoing conversations among the authors and followed an abductive approach (Yanow and Schartz-Shea, 2006). Already during fieldwork, the study gradually gained focus as it became evident that scientists spent much time working in their disciplinary subgroups (i.e. bioprocessing, electronics and sensors), relying on a number of processes of knowledge integration. This phenomenon henceforth became our focus (Eisenhardt and Santos, 2000, Majchrzak et al., 2012, Schmickl and Kieser, 2008). Second, two aspects of the scientists' practice surfaced as particularly relevant for knowledge integration, namely the dialogic interactions in meetings and the material mediation of their work through artefacts (these two foci evolved into two papers with the present one focusing on the former). Third, we witnessed scientists changing quite radically their mode of working together with the unfolding of the project as the working apart mode later changed into a more intense collaboration.

Once we identified this apparent gear change as our 'empirical puzzle' (Timmermans and Tavory, 2012: 177), we started to compare and contrast our data in temporal terms asking ourselves critically what exactly changed in the mode of integrating knowledge and why it happened. While the three authors had initially worked independently to identify, inductively, recurrent themes, challenges, practices, and interactional patterns (King, 2012), we now empirically compared the several occasions when scientists faced an ‘unanticipated result’ with the one occasion that seemed a different case - an ‘inexplicable result’ - that meant scientists had to start collaborating more intensely. We moved towards a more explicative phase (Yanow and Schartz-Shea, 2006) when the comparison became informed by the literature on knowledge integration and we asked how ‘epistemic uncertainty’ (Dougherty and Dunne, 2012, Grandori, 2010) separated the one ‘inexplicable result’ we observed from the others and how this informed the change in practices of knowledge integration. We framed the occurrence of the ‘inexplicable result’ as a ‘breakdown’, and started to compare how the breakdown was similar or different from previous breakdowns discussed in relevant process literature (Sandberg and Tsoukas, 2011). We also analysed how the meetings changed according to more theoretically informed themes, in particular how distinctions were drawn in dialogue (Tsoukas, 2009, Tsoukas, 2008). We did so, first by examining our data for distinctions being drawn (e.g. distinctions between the ‘measurement problem’ and ‘the stem cell problem’), and then by developing more abstract categories (e.g. distinctions between ‘the known and unknown’). The comparative and abductive work continued well into the writing phase when we decided to organise our findings around two research questions:

‘how do specialists from diverse disciplines integrate knowledge when they are faced with epistemic uncertainty, and how does dialogic work support knowledge integration in such settings?’

Findings

The interdisciplinary group of scientists had embarked on a complex and very novel task. It worked with adult stem cells from bone marrow and wanted to develop a controlled system that could monitor the complex set of interacting conditions that allowed the non-specialized cells to differentiate into blood cells. The project was challenging because the differentiation of stem cells depends on multiple interacting variables, such as, the cells’ wider physiochemical environment (i.e. pH levels or temperature), nutrients and metabolites (i.e. glucose, ammonia, lactate), and growth factors (i.e. stem cell factors, Flt3-ligand). At the time of the study, the underlying science was untested and the effects of the interaction among these variables were largely unknown. The project involved 18 scientists from different disciplinary backgrounds from electronics to bio-processing, biochemistry and proteomics. The team was organized in three sub-groups: the sensor, the electronics and the bioprocessing teams, each working on a specific task defined with clear deliverables (see Table 1).

INSERT TABLE 1 ABOUT HERE

The knowledge integration process

Our findings suggested, first, that knowledge integration was not a homogeneous process, but one characterised by different practices. As noted above, for a considerable amount of time the scientists collaborated mainly at a distance from their respective laboratories working 'together-alone' (Bruns, 2013, Enberg et al., 2006). While problems inevitably arose during this time, they were dealt with rather quickly without the need for intensive working together. Yet, when the scientists were faced with an 'epistemic breakdown', their knowledge integration practices changed quite dramatically, The epistemic breakdown we observed was a profoundly unsettling event that emerged out of the interaction of a series of unforeseen problematic issues that could not be solved by drawing on the existing knowledge of the individual disciplines. It required scientists to continue working with their discipline-specific practice (e.g. conducting experiments), *and* to abandon their established ways of integrating knowledge (together-alone) by engaging in a more intensive, dialogue-centred practice of drawing distinctions.

Below we analyse this shift in the mode of knowledge integration in detail. By way of overview we show, first, how scientists attempted to address the 'coordination problem' of knowledge integration by working together-alone. We then illustrate the change in knowledge integration practices by showing, second, how the scientists faced the epistemic breakdown by dialogically (re)drawing distinctions, thus engaging in a generative process of knowledge integration. Finally, we show how the scientists reverted to a more co-operational mode of knowledge integration once they had managed to circumscribe the breakdown they were facing.

Addressing the coordination problem by working together-alone

A bioreactor of this kind had never before been attempted and the scientists had very limited knowledge about the conditions for cell growth or what sensitivities and precisions for measurement might be useful. Despite this, the senior scientists approached the undertaking as 'just another project' (Principal Investigator). Accordingly, at the beginning of their collaboration, the group performed their habitual practice of establishing goals and clarifying mutual interdependencies using a project plan that defined work packages and methods for interacting (Bengtsson et al., 2011; Knorr Cetina, 2008: 94).

> *'We [bioprocessing specialists] gave our colleagues really high specs. (…) We were very, very strict in the sensitivity that we wanted to measure. In this way, the errors*

that we would be going to have could be attributed to almost a 100% to bioprocessing, not to electronics, not to sensors.' (Principal Investigator)

Early on, the bioprocessing group developed a table with precise parameters defining, for example, that the bioreactor had to '*measure glucose from 1 to 10 millimole, with a measurement error of no more than 10%*'. Such deliverables were defined through repeated meetings among the three specialist sub-groups. Each sub-group produced an initial '*wish list*'. The list was then discussed in view of the capacity of the respective laboratories and the state of the literature to establish what was possible. By negotiating the parameters that would work for the various sub-teams and establishing a protocol that served as a common ground and term of reference, the group were addressing knowledge integration as an issue of coordination,.

This, in turn, allowed the researchers to work in relative independence, or 'working alone together' as Bruns (2013) calls it. As scientists expressed: '*We have got distinct work'; 'He is not really involved because he has done his bit'; 'I don't need to learn how to make sensors or how to make electronic boards. They know how to do it' (from field notes).* Reciprocal lab visits were very rare and the integration work carried out during these early meetings was mostly limited to updating each other on mutual progress (cp. Enberg et al., 2006): *'It tends to be very much reporting (...) this is what I'm going to do next'*

(Senior Sensor Specialist). Each sub-team used brief PowerPoint presentations and engaged in ‘displaying’ and ‘representing their work’ (Kellog et al., 2006), ‘voicing fragments’ (Majchrzak et al., 2012) of the present challenges and solutions they were currently working on. For example, during one of the monthly meetings, the sensor sub-team presented their planned experimental design and set up, showing visual models of where they were to place which sensors in the bioreactor for the various experimental conditions. Others attending the meeting acknowledged this matter-of-fact presentation in silence, only occasionally asking short factual questions. For example, the senior bioengineers asked: ‘*What is the cell seeding density you worked with?*’ or ‘*What FBS concentration did you have in the media?*’ Such questions were answered with other brief, matter of fact answers.

The initial interaction, then, was oriented towards participants learning about each other’s progress and ‘deep-knowledge dialogues’ (Majchrzak et al., 2012) were notably absent. When a problem surfaced, it could be solved by the specialists looking for a solution within their respective disciplines and continuing with their domain-specific practice (e.g. adopting different sensing technologies). There was little need to go beyond disciplinary boundaries to address the problems that regularly emerged. The scientists’ collaborative efforts oriented towards stabilizing objectives and mutual dependencies, thereby addressing the coordination problem of knowledge integration (e.g. voicing problems/solutions, see: Majchrzak et al., 2012) and working 'together-alone' (Bruns, 2013). This radically changed, however, when the group encountered a major breakdown.

Facing an epistemic breakdown

In May of their second year of collaboration, the scientists faced a major, seemingly irresolvable breakdown and for the following six months they had to engage in a different, and until then unobserved, practice of knowledge integration. The breakdown occurred when the group had assembled the different subparts of the bioreactor, had started to conduct the first experiments and was faced with a series of interconnected and entirely unforeseen problems. Consider these field notes from a project meeting:

> *There is a lot of excitement as last week, after months of work to design, build and assemble all the parts, they have finally run the first experiment. Things, however, have not gone smoothly. The issue is that readings are very different from what was expected. They make little sense and point in all sorts of possible directions. Are the predictions wrong? Is the proteomics machine acting out again? Is the electronic board faulty? Are the sensors not working?*

Scientists were not able to make sense of the situation by drawing on their own disciplinary knowledge. The situation was deeply unsettling as it was not clear what the problem was or what the relevant parameters were – was the issue related to the sensitivity of the electronic board, the longevity of the sensors, the bridge between the sensors and the bioprocesses, cell contamination, their initial predictions being just wrong, or any combination of things?

We call this type of breakdown ‘epistemic’ because it opens up epistemic uncertainty such that holding onto previously-held, discipline-specific ways of knowing is not sufficient to address the breakdown. This also meant that it is unclear which disciplinary domain is responsible for resolving the breakdown and scientists could no longer revert to their established mode of working together-alone. The situation required a shift in the knowledge integration process, which entailed several iterative cycles of drawing distinctions in dialogue.

Drawing distinctions in dialogue – which differences make a difference?

In the weeks ensuing the epistemic breakdown, the group tried to get a handle on things by conducting further experiments. Yet, things remained very fuzzy. Slowly, but observably, the group changed the way it interrelated during, and between, meetings. Researchers started to talk more frequently and reciprocal lab visits increased in number and duration. The quality of the interactions during meetings also underwent a significant change. Overall, the collective attention started to be focussed on identifying ‘differences that could make a difference’ (Bateson, 1972), as we will illustrate below.

During one of the monthly meetings, the junior bioprocessing specialist shares the results of an experiment his team had run for seven days with four parallel bioreactors, comparing a system with profused cell cultures, static cells and a control group. The interdisciplinary group engages with these results through the dialogue below [emphases added]:

Senior Electronics Specialist: *I need to understand. Let's take the two yellow lines that show the biggest **difference**, which is channel 8 of bioreactor 1. Does it mean anything that ammonia drops?*

Junior Bioprocessing Specialist: *I don't know why it dropped.*

Senior Bioengineer: *Shouldn't it go up? (...)*

Junior Sensor Specialist: *I don't care if it is more negative or more positive. (..) It's just that we look at the **difference**, but actually from the picture it means that suddenly the concentration of ammonia dropped and I'm wondering why.*

Senior Electronics Specialist: *So if it goes down it means the concentration goes down?*

Junior Sensor Specialist: *Yeah, the concentration goes down.*

Junior Bioprocessing Specialist: *We don't know why here it goes up.*

Senior Electronics Specialist: *Yes, but this is something else. That's **different**.*

The group focuses its attention on the striking differences in the data ('Let's take the two yellow lines that show the biggest difference', 'It's just that we look at the difference') and inquires what these differences mean (‘I don’t know *why* it dropped, ‘I’m wondering why’) and how they can be explained. As none of the scientists knows the solution to the problem (consider the several open questions in the extract), their effort is to identity those differences that could actually make a difference. This is achieved by interactively drawing distinctions between, on the one hand, what is *relevant* to resolve the breakdown vis-à-vis what is *not relevant,* and, on the other, what is *known* and what is *unknown*.

Drawing distinctions between the relevant and irrelevant

Dialogue was used to establish which distinctions needed to be made first and which could be left open a bit longer. One example of this process is provided in the extract below. The senior electronics specialist openly admits that they have problems with the glucose sensor and that they did not manage to meet the resolution requirements the bioprocessing team had asked them to:

Senior Electronics Specialist: *This is not quite the 1 millimolar resolution that you were asking us (...). It is difficult for us.*

Senior Bioprocessing Specialist**:** *I know that, but I think what I’m trying to say is that because this is completely new, and because we’re going from no information to 5 millimolar resolution, it’s a huge, huge improvement,* ***so it doesn’t even matter.*** *I think more important is to be able to get a signal that works … rather than being* *able to determine that, let's say, 25 millimolar concentration is better than 23 millimolar concentration.* (emphasis added)

What the electronics group believes constitutes a problem for the bioprocessing team (i.e. not achieving the required accuracy), gets reformulated by the bioprocessing specialist as not being a problem at all! The dependencies between the two disciplinary sub-groups, which had been determined at the beginning of the project, are now open to question. What is interesting here is that the group does not develop more fine-tuned distinctions (cp. Tsoukas, 2009, Tsoukas, 2008), but rather, loosens up previously-held distinctions. For example, the bioprocessing specialist makes an argument for *less* determination and coping with a 'grey zone'. 'Because this is completely new', he suggests, fine distinctions do not need to be drawn and rough ones are sufficient. He explained his reasoning as follows:

I'm trying to say... It won't make that much ***difference****. (..) First of all, you're going to have a 'grey zone' to begin with biologically speaking. No matter what,* ***it doesn't matter*** *what kind of resolution you have, we would have a grey zone, where the cells, they sense things; they may go to alternative networks. (..) Nobody has really defined that grey zone, and even if you could, you don't know what the cell would do. Definitely 5 millimolar is not unusual. We will never be* *able to pick up any of these cells (..). So it's not a problem at all.* (Senior Bioprocessing Specialist emphases added).

The bioprocessing specialist attempts to convince the others that, in this highly novel context, it is not productive to narrowly determine the distinctions made, as before. He therefore uses the image of a 'grey zone' to argue that at this stage, things should be left rather fluid as drawing finer distinctions would not make a difference for the collaboration ('*it doesn't matter*'). Such moves to loosen, rather than fine-tune (cf. Tsoukas, 2009), distinctions also meant that the dependencies among the work of the different sub-groups were loosened up during the protracted period of the epistemic breakdown.

Drawing distinctions between the known and the unknown

A second way of drawing distinctions during the period of the epistemic breakdown was to discern, collectively, the known from the unknown. Consider the following exchange during a monthly meeting that took place two months after the examples above. A relatively junior (post doc) bioengineer presents the results of the latest experiments which, again, went wrong: '*unfortunately one of these sensors went bad again for whatever reason' he says. 'We're not quite sure. You see this weird trend. It just starts dropping.*' After a brief exchange the junior sensor specialist gives a hint as to where the problem might lie:

Junior Sensor Specialist: *We just need to connect the sensors better because I think the connector was too heavy and pulled.(..)*

Senior Bioprocessing Expert: *And the position of the sensor makes sense as well, right..?*

Junior Bioengineer: *Yes, you can see a difference definitely (...)*

Senior Electronics Engineer: *In the previous drop, are the values taking into account calibration?*

Senior Bioengineer: *Have you done any processing on the raw data? You find a calibration effect where you raise them to the power of 10.*

In this exchange it is again apparent that none of the disciplinary domains holds the solution to the mystery faced and that the issue seems to be beyond the limits of each researcher's horizon of understanding. Only collectively can they find some indications of which parameters (e.g. weight of connector, position of sensors, calibration) might help them delineate the problem. This is achieved by openly admitting that they do not know ('We're not quite sure') and then asking rather precise questions ('Are the values taking into account calibration*?'*) to which precise answers are given ('you find a calibration effect'). The example shows how the researchers dialogically 'weed in' (Dougherty, 2007: 266) possible aspects that might allow for encompassing the 'weird trend' that is still collectively unknown and gradually transform it to become known. Their knowledge integration practices now go beyond coordination efforts, entailing a joint effort to work their specialist knowledge together and expand it. This effort is beyond disciplinary boundaries; as you can note it is the bioengineer, not the electronics specialist, who links the calibration effect to a power (voltage) issue. Once initial distinctions between the known and unknown had been established tentatively in dialogue, further work was needed to test these distinctions and the group agreed to re-design and conduct further experiments.

Addressing the cooperation problem by enacting a new distribution of expertise and ignorance

The growing clarity around which distinctions mattered and what was known/unknown allowed the group to move away gradually from their dialogue-intensive mode of integrating knowledge. In other words, as the breakdown's epistemic uncertainty was transformed into a problem with at least tentatively identified parameters, the group moved back to dealing with the issue of coordinating their respective work. They now appeared to work, however, in a more political fashion, in the sense of aligning expectations and obligations typical of the 'co-operation problem' (Tell, 2011), as we explain next.

The establishment of new distinctions brought with it new expectations amongst team members as to those who were granted jurisdiction on a specific aspect of the breakdown needed actually to deliver a solution. Negotiating and consolidating the redistribution of expertise and responsibilities constituted a critical step to re-establish the together-alone mode of collaboration. An example can illustrate this point:

After months of effort, the scientists had established that the breakdown could, in part, be attributed to the sensors' insufficient longevity. Yet for another three months, the sensors team failed to deliver sensors with sufficient longevity. While the bioengineering and electronics teams were careful not to '*come across as if it were...well, we were putting them [the sensors' team] on trial or something like that*' (senior bioengineer and project manager), with time frustration rose and doubts began to emerge.

> *'I don't know if it's that their bit is harder to do or it's because they just… I don't blame them, but I just say… every time they report they say, next time we are going to do this, this, this and this, and then at the next meeting nothing turns up ...'* (Junior Bioprocessing Specialist)

The expressed doubt ('I don't know if it's that their bit is harder') is no longer an admission of ignorance and/or a way to seek help from other disciplinary domains. Instead, the ignorance about the difficulties of the sensors' team is used to underline the responsibility of the sensors' team and to reinforce disciplinary boundaries. Not being able to judge the level of difficulty faced by the sensors' team, the bioprocessing and electronics teams started – albeit cautiously - to attribute the failure to a lack of commitment. As the senior bioengineer told us: *'The biggest problem is, and it is an impression, that there isn't the commitment from the sensor side of things.'* Suspicions of incompetence also started to surface. For example, we observed the senior electronics specialist querying a junior sensor specialist over the sensors' longevity problems:

Senior electronics specialist: *'How many points do you usually use for calculation?'*

Junior sensor specialist: *'It's not… If you would like to see it, you are welcome.'*

Senior electronics specialist: *'I'm just trying to understand how you work.*

While in earlier stages of the collaboration, open technical questions like '*How many points do you usually use for calculation?'* were heard as a way to learn about each other's progress (i.e. 'together-alone' phase) or to delineate the boundaries of the problem (i.e. 'drawing distinctions in dialogue' phase), they were now heard as a signal of growing mistrust. As such, they were received as an inappropriate attempt at control, as underlined also in a later interview with the junior sensor specialist.

'It's just that there was too much stress put on the sensors. Every meeting we would hear: 'we want sensors, we want sensors'. It's very hard to meet the requirements

because it's the most sensitive part. Maybe sometimes they expected a kind of miracle from us. That could be a little bit annoying.'(Junior sensor specialist)

The example shows that with the problem now being circumscribed, disciplinary boundaries were marked again more clearly and interdisciplinary interventions resisted. Knowledge integration become a more political endeavour of aligning mutual expectations and obligations. Allegations of 'incompetence' eventually led to the mutually agreed-upon decision to add a more senior sensor specialist to the sensors' team. The move reinforced disciplinary boundaries not only discursively, but also materially. By doing so, the interdisciplinary project team was able to gradually move back to a mode of knowledge integration oriented towards the coordination problem and working 'together-alone'.

Discussion

In this paper, we have shown that knowledge integration through (re)drawing distinctions in and through dialogue is critical when trying to tackle epistemic uncertainty as in such conditions coordinating and translating knowledge may not suffice. This mode of knowledge integration is triggered by an epistemic breakdown – a deeply unsettling event, cognitively and emotionally, where the hitherto-held understandings and ways of knowing the problem appear unworkable. When epistemic breakdowns occur knowledge integration shifts from a more coordinative mode of 'working together alone' (Bruns, 2013, Enberg et al., 2006) to one where the generative quest of knowledge integration becomes central and where collective knowledge is expanded through intensive dialogical work oriented toward drawing distinctions.

Our findings allow us to propose a new processual framework for knowledge integration, shown in Figure 1.

INSERT FIGURE 1 ABOUT HERE

The framework depicts knowledge integration as a process entailing an 'ensemble of different types of practices' (Bruns, 2013: 78) that shift depending on the particular challenges that emerge during the innovation journey. Epistemic breakdowns play a crucial role in the shift from 'working together-alone' to a more intensely collaborative practice of drawing distinctions in dialogue by recursively separating out the relevant from the irrelevant and the known from the unknown. This continues until it becomes clear which new distinctions matter so that a new 'geography' of distinctions can be established. This new geography is critical as it allows a revised division of labour and responsibilities to emerge. Only once distinctions are (re)established can collaborators start to focus, again, on the coordination problem of knowledge integration and who is responsible for what (Tell, 2011).

We contribute to the literature in a number of ways. First, our study offers a processual view of how collaborators integrate knowledge and navigate their way through epistemic uncertainty. In line with other advocates of process-based studies in organization (Langley et al., 2013), we do not see an epistemic breakdown as some kind of exogenous event that ‘happens to people’ with, more or less, instantaneous effects. Rather, our study shows that epistemic breakdowns emerge from collaborative work when things start to appear to collaborators as inexplicable, such that they no longer know how to go on and intensely experience epistemic uncertainty. Finding a way out of the epistemic breakdown is not obtained, either, instantaneously through some kind of mental ‘switch’ or through ‘fleeting moments’ of collective creativity (Hargadon and Bechky, 2006: 497). While these ‘aha’ moments may be important (Napier et al., 2008), in our case collaborators felt like they were navigating in ‘a labyrinth’ (Dunne and Dougherty, 2016) - an intricate complex of events where it was not possible to see the way out. The epistemic breakdown thus required a slow and patient effort of re-making distinctions collectively. Drawn distinctions were often tentative and required an iterative process of developing new distinctions in dialogue and of materially testing distinctions by staying engaged in the (scientific) work.

Our second contribution is to articulate the concept of 'epistemic breakdown' showing how this plays a critical role in driving a shift in the mode of knowledge integration. We argue that the characteristics of an epistemic breakdown, seen above, set it apart from other types of breakdowns discussed in the literature on knowledge and learning. In particular, the breakdown we observed is different from both the 'temporary' and the 'complete' breakdowns outlined by Sandberg and Tsoukas (2011). The authors suggest that while temporary breakdowns require practitioners to examine what they do while remaining engaged in the practical activity – what they call 'involved thematic deliberation' - compete breakdowns, ask for a 'theoretical detachment' as the practitioner has to interrupt his/her practical work and reflect upon it in a more detached theoretical manner (p. 344-345). In our situation, however, it is neither through 'thematic deliberation' (Sandberg and Tsoukas, 2011: 344) nor through 'theoretical detachment' (Sandberg and Tsoukas, 2011, Hargadon and Bechky, 2006: 345) alone that an epistemic breakdown can be overcome. Rather, when epistemic breakdowns occur, practitioners must continue their discipline-specific practical work, and at the same time must engage in an intensive, dialogue-centred practice of drawing out new distinctions. The epistemic breakdown occurring at the interstices of disciplinary work thus requires actors to hold on to the established disciplinary practice but, at the same time, find new ways of interrelating between disciplines in order to develop new understandings.

This relates to recent work (Deken et al., 2016) that showed how breakdowns, stemming from interdependencies between routines that lead to different understandings, can contribute to the variation of routines. In our case, epistemic breakdowns invoked shifts in the mode of collaborating itself; collaboration became more intensively dialogical, for a time. This suggests that breakdowns may play a critical role, not just in changing routines and initiating further sequences of collaboration, but also in temporarily changing the nature of collaboration itself. It is not only *whether* a breakdown occurs that matters to the pursuit of knowledge integration, but also *what kind* of breakdown is collectively experienced, when it occurs and for how long. Further research is needed to explore which knowledge integration practices are relevant when dealing with breakdowns across other contexts. In our context of scientific experimentation, epistemic breakdowns were material and highly visible and further research could analyse how breakdowns shape knowledge integration in contexts, such as the service industry, where material manifestations are (arguably) less visible.

A third, major contribution of our study has been to show and better understand the dialogic work entailed in knowledge integration. Our study reveals the dialogic practices that collaborators used to 'reach forward' to the unknown and 'weed in' alternative explanations from their diverse disciplinary backgrounds (Dougherty, 2007: 266) and to collectively generate *new* distinctions to gradually tackle the epistemic uncertainty they faced. Interestingly, knowledge was expanded not only by refining, but also by loosening previously-held distinctions (cp. Tsoukas, 2008). This generative aspect of knowledge integration required actors to (temporarily) embrace a 'grey zone' where dependencies were opened up. This finding complements recent work by Dunne and Dougherty (2016) who foregrounded how 'abductive reasoning' in complex innovation processes enables innovators to focus their search while encompassing enough of the uncertainty' necessary to address inevitable crises (p. 150). Our study suggests, further, that when crises do happen, collaborators also need to question their underlying distinctions and that the challenging and conjecturing of distinctions happens mainly in conversations as a collective process (Tsoukas, 2009).

Whilst pointing to the role of dialogue for knowledge integration, our study does not suggest that the epistemic breakdown could have been resolved solely through dialogic practice (cp. Bosma et al., 2016). On the contrary, scientists continued to engage in their practical work (e.g. doing experiments) and to draw on material resources to test the dialogically drawn distinctions. Practical work, mediated through material objects, thus also played a significant role (Carlile, 2002, Swan et al, 2007, Nicolini et al., 2012). In this sense, the process outlined in Figure 1 is itself grounded in, and dependent upon, a background of ordinary practices that allow scientists to go on searching and experimenting. Similarly, even in the most extreme situation of an epistemic breakdown, our scientists shared a scientific approach, language, and methodology, as well as a clear sense of what it meant to be a 'good' scientist within a reputable institution. These structural elements may explain, in part, why our scientists were able to engage in the dialogic practices and ask meaningful questions beyond one's domain of expertise. Future research would be needed to inquire critically into the roles of dialogue for innovation in highly novel settings where this common ground might not equally be taken for granted.

Finally, our study points to the affective, pragmatic and political quality of knowledge integration processes. It has been recognized that knowledge is 'at stake' when practitioners try to work across boundaries created by specialist practice (Carlile, 2002). Our study suggests that facing epistemic uncertainty is also emotionally laden. Not only do breakdowns generate anxiety and discomfort, once initial and tentative distinctions are established, further difficulties can be cast as doubts about mutual commitment and even competence. The attribution of expertise, and the acknowledgment of specific jurisdictional rights, go hand in with the expectation that collaborators will be able to deliver what is admittedly within their remit. Failure to do so is interpreted, not as a cognitive failure, but as a moral wrong. The lesson from our case is that in knowledge integration processes expertise, jurisdictional politics and moral judgement go necessarily hand in hand. Further research could examine further these affective and political aspects of knowledge integration.

Conclusion

Our study has offered a processual account of knowledge integration in interdisciplinary collaboration, suggesting that knowledge integration is not a homogenous process, but one that is characterised – over time –by different practices to cope with different types of challenges. We have shown that the practices of knowledge integration change during the same project and depend on the nature of breakdowns experienced. When collaborators meet an ‘epistemic breakdown’, they can no longer rely on a together-alone mode dealing with coordination issues of knowledge integration alone, but have to tackle the generative quest of reaching forward towards the unknown by collectively drawing distinctions in dialogue. Our study thus contributes to a critical reflection on the role of dialogue in knowledge integration, showing how the dialogic practice unfolds when collaborators are faced with epistemic uncertainty.

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Figure and Tables

Table 1: The tasks and major challenges of the specialist groups developing a bioreactor for controlled stem cell growth.

	Sensors Group	**Electronics Group**	**Bioprocessing Group**
Task	Develop sensors for the various stem cell nutrients: glucose, metabolite, lactic acid, ammonia, temperature, PH, oxygen	Fabricate an electronic board of 16 channels (both in terms of hard and software), which can read the signals from the sensors, clean them from noise, amplify and digitize them and communicate them to a computer.	- Set up protocols for cord blood stem cultures along three dimensions (culture parameters, cell types, cell functions), which allows to purify stem cells, culture them and analyse them with various techniques - Develop design for experiment strategies
Major Challenges	- Achieve specified sensor sensitivity: sensitivity continued to drop by more than 70%, instead it would have been needed to stay stable - Achieve specified sensor longevity: increase longevity from a few hours to at least five days in order to have enough time to grow mature cells from stem cells.	- Achieve high parameters of sensitivity and accuracy of board in order to guarantee a low tolerance of error - Develop a reliable bridge between the sensors and the bioprocesses: · Miniaturize size and weight of connector clips · Find a solution for robust, but light electronic wires connecting the sensors with the electronic board (eventually develop a wireless transmitter)	- Avoid contamination of cells through bacteria, which was particularly challenging as sensors had to be introduced in an in vivo environment

Figure 1: Knowledge integration process in the face of epistemic uncertainty