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Anticipatory Work: How the need to represent knowledge across boundaries shapes work practices within them

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Abstract

Representations, such as graphs and images, have been shown to help facilitate communication and coordination across knowledge boundaries. Many studies examine representations' effects during and after interaction, characterizing them as tools that help communicate local understandings with individuals who have differing knowledge. This study explores whether the anticipation of building representations to communicate across knowledge boundaries significantly shapes a community's work. To explore this question, it develops a theoretical framework extending MacKenzie's (2006) appropriation of performativity and presents ethnographic data from four weather research teams collaborating with different organizations to develop tailored forecasting technologies. Analysis reveals that researchers' need to represent weather model outputs to their partners shaped the practices they used to produce those models. By uncovering the presence and influence of "anticipatory work," the findings paint representations not as passive communicators of established knowledge, but as catalysts that shape the form of routine work.

Keywords: Anticipatory Work, Data Representation, Knowledge Boundaries, Performativity, Technology, Organizational Communication

Research on communication at knowledge boundaries has demonstrated the validity of the adage that a picture can be worth a thousand words. When individuals from different backgrounds seek to develop novel ideas, design new products, or make difficult decisions together they find frequently that differences in understandings, work practices, and values produce boundaries that limit their ability to share knowledge (Brown & Duguid, 2001; Kotlarsky, van den Hooff, & Houtman, 2015; Neff, Fiore-Silfvast, & Dossick, 2010). In these situations, pictures, or other data representations like figures, graphs, or material objects, can help convey information that would be difficult to express through talk alone (e.g. Star & Greisemer, 1989). Studies show that representations can help people communicate to achieve shared understandings (Bechky, 2003b; Carlile, 2002), enlist support (Bechky, 2003a; Latour, 1986), and coordinate how work should proceed (Henderson, 1998; Swan, Bresnen, Newell, & Robertson, 2007).

Although pictures and other representations can help individuals communicate across knowledge boundaries, they do not simply appear when the need arises. An overlooked extension of the above-mentioned adage might read: …but producing the right picture can take a thousand words' work. People actively search for, select, and produce the representations they apply in their interactions with others. Recent studies have shown that people spend a great deal of time thinking about how to represent their data to other groups and building representations they believe will help achieve their goals (Barley, Leonardi, & Bailey, 2012; Kaplan, 2011; Stark & Paravel, 2008). What these studies do not show is that the work necessary to prepare representations for future interactions may not always be as simple as sitting down to create the table, chart, graphs, or object, and then returning to work as usual. When studying interaction at knowledge boundaries, we often treat data representations and the work of their production as afterthoughts to work occurring within knowledge boundaries.

This study challenges this assumption by asking whether efforts to produce representations that will help communicate across knowledge boundaries lead individuals to shape their own work practices. That external representation work might influence internal work practices becomes relevant when considering research from science and technology studies showing that data representations are just as central to work within knowledge boundaries as they are to interaction across them. We know that representations play a role in establishing goals (Knorr-Cetina, 1997, 1999; Rheinberger, 1997), standardizing and maintaining common practices and values (Daston & Galison, 2007; Galison, 1997), and negotiating the direction of future inquiry (Latour, 1986, 1990; Vertesi, 2014).These findings suggest that representations are more entangled with the work surrounding knowledge boundaries than we often consider.

Taking a practice orientation toward work at knowledge boundaries (Bechky, 2011; Bruns, 2013), I extend MacKenzie's (2006) notion of performativity to develop a framework theorizing how the anticipation of representing data in future cross-boundary interactions may lead people to shape their own work practices. To explore how individuals' anticipate data representations, I present a field study of weather researchers at a national research lab that developed computational forecast models to generate weather predictions that would be useful to their applied partners. My findings demonstrate how, with an eye toward future representations, researchers shaped their work practices so they could produce data that could be represented across knowledge boundaries. Where prior studies have shown that people make representations of their work, this study suggests people make their work for representation.

Background

Boundaries among groups of specialized workers are a prominent characteristic of complex social organizations (Abbott, 1995; Aldrich & Herker, 1977; Simon, 1997; 1947). Beginning as early as with the Carnegie School (Cyert & March, 1992; March, 1962; March & Simon, 1958; Simon, 1997; 1947), theorists recognized that specialization, while necessary to negotiate complex environments, also produced organizational subunits with localized knowledge and goals. Managing this fragmented knowledge requires boundary-spanning mechanisms to make decisions, coordinate activity, and innovate (Ancona & Caldwell, 1992; Carlile, 2004; Galbraith, 1973; Okhuysen & Bechky, 2009). A persistent tension in this space has been the recognition that the same qualities that enable specialization's benefits, such as distributing tasks among relevant experts, often hinder knowledge sharing (Lawrence & Lorsch, 1967; Leonard-Barton, 1992).

Recently, this tension has gained attention from scholars adopting a practice perspective to understand communication at knowledge boundaries (e.g. Bechky, 2003b; Faraj & Yan, 2009; Kellogg, Orlikowski, & Yates, 2006; Levina & Vaast, 2005; Majchrzak, More, & Faraj, 2011). A practice approach identifies communities, and the boundaries dividing them, based upon the presence or absence shared work practices rather than formal position within an organization's hierarchy (Brown & Duguid, 1991; Lave & Wenger, 1991; Wenger, 1998). When people seek to share knowledge with people who have differing experiences and values these differences can create boundaries that make communication difficult (Brown & Duguid, 2001; Dougherty, 1992). Carlile (2002, 2004) showed that as the knowledge boundaries dividing actors increased in complexity, the effort required to communicate increased. He described three types of boundaries: The simplest, a syntactic boundary, occurs when communicating parties share enough common syntax to communicate using simple information transfer. When communities have differing expertise differences in base knowledge may render local information incomprehensible. At such semantic boundaries, communication requires translating understandings to be meaningful across boundaries. The most complex boundary, a pragmatic boundary, involves the presence of value differentials that must be resolved via negotiations prior to joint action.

Studies of interaction at knowledge boundaries have shown that data representations as diverse as maps (Star & Greisemer, 1989), sketches (Henderson, 1998), tables and charts (Carlile, 2002), blueprints (Ewenstein & Whyte, 2009) and physical parts (Nicolini, Mengis, & Swan, 2012) can help mitigate some of these communication difficulties. When incorporated into discussion, these objects not only display information but embody the local theories, understandings of the world, and work practices of the individuals who produced them (Hutchins, 1995). A representation such as a physical part, can provide a focal point for discussion, illuminating differing perspectives to help people develop shared understandings for how work should proceed (Bechky, 2003b). Representations also help to make domain knowledge meaningful across boundaries. Drawing on observations of engineers designing engines and medical instruments, Henderson (1999, p. 198) argued that visual representations "elicit tacit knowledge from participants so that it can be represented in formats readable to others." Carlile (2004) showed how a 3-dimensional computer simulation allowed automotive engineers with differing knowledge to translate ideas and address design conflicts earlier in the vehicle production process. Swan, Brenson, Newell, and Robertson (2007) found that the joint manipulation of draft research protocols permitted scientists and clinicians working on a genetics research project to overcome practical knowledge differences. By interacting around these questionnaires, workers were able to produce a protocol incorporating scientists' research principles in a format allowing easy clinical administration.

Although research has shown that representations play an important role in communication across knowledge boundaries, studies have disproportionately emphasized how they are used in moments when individuals are engaged actively in interaction. This interactional bias is present in much of the literature on work at knowledge boundaries, which tends to study formal meetings (e.g. Beck & Keyton, 2009; Carlile, 2002), or impromptu gatherings (e.g. Bechky, 2003b; Faraj & Xiao, 2006). By foregrounding interaction, research tends to examine how representations affect work during and after the moment of their negotiation. For example, the 3-D models in Carlile's (2004) study only made interdependencies visible once introduced into active design negotiations, ultimately leading to the effect of reducing engineering time by 30% and costs by 50% (p. 562). The engineering drawings in Henderson's (1999) study only made tacit understandings visible once introduced in meetings. By focusing on interaction, prior research characterizes representations as media that passively convey pre-existing knowledge to facilitate social negotiations and change.

Such an information processing perspective toward communication has been questioned as organizational scholars have recognized increasingly that the practical requirements of communication can shape the ongoing process of work (e.g. Ashcraft, Kuhn, & Cooren, 2009; Cornelissen, Durand, Fiss, Lammers, & Vaara, 2015; Kuhn & Jackson, 2008; Leonardi & Barley, 2011). Others have argued that expanding the scope of our research to encompass broad work processes can reveal new theoretical nuances (Bechky, 2011). Bruns (2013), for example, suggested scholars should take a process orientation to consider how efforts to interact across knowledge boundaries bleed into the work outside of interaction. Following collaboration among experimental and computational systems biologists, she revealed that collaborating with scientists from different knowledge backgrounds led researchers to think differently about how they approached their own scientific practice. Where most research on representations has shown that representations help transmit existing knowledge across boundaries, a perspective acknowledging the performance of work around those objects might also reveal that they shape work, and potentially knowledge, within boundaries.

An Anticipatory Performative Perspective on Representation Work

Exploring how representations play into the broader process of work at a knowledge boundary requires a framework connecting those objects with work practices outside of interaction. MacKenzie's (2003, 2006; MacKenzie & Millo, 2003) appropriation of the concept of performativity provides such a theoretical tool. Performativity was first introduced by J.L. Austin (1961, 1975) to describe communicative acts that went beyond stating information to perform meaningful social actions. A canonical example being that when an admiral says, "I name this ship the Queen Elizabeth" they not only state the ship's name but, given proper context and authority, actually perform the act of naming the ship (Austin, 1961, p. 222). A performative utterance moves beyond the simple transfer of information to produce a change in the surrounding social world. MacKenzie (2006) appropriated and extended performativity for use in studying knowledge representations. Rather than viewing representations as "cameras" that passively convey a static image of a realist world, he argued we should think of representations as "engines" that may lead people to perform the image of the world they portray (p. 12).

MacKenzie illustrated this perspective by tracing of the influence of financial simulation models and their representations on trading practices in the U.S. stock market. Taking a historical approach, he demonstrated how the Black-Scholes-Merton Model of Options Pricing engendered changes in traders' investing strategies. This economic model was one of the earliest to predict future option values given current prices and an estimate of market volatility. Perceiving a potential trading edge, investors began bringing crib-sheets of the Model's outputs with them into Chicago's trading pits. MacKenzie showed that during early phases of their adoption, these representations functioned very poorly as cameras of market behavior: the Model's predictions erred significantly from observed market pricing. As the trading sheets grew in popularity, however, the market's pricing patterns shifted in a way that actually increased the model's accuracy. When traders bought and sold stock using the predicted values on their crib sheets, their actions pushed the actual stock's value toward the model's predictions (pp. 164-166, 256-259). Investors' recurring use of these representations altered their trading performance (i.e. their work) to mirror the world the Black-Scholes-

Merton model displayed. The representations influence performance in a way that made their world a reality.

In MacKenzie's analyses, a representation's potential for performative influence occurs over the time after it is introduced into work. If we seek symmetry in our orientation toward work at knowledge boundaries it is equally important that we explore performative mechanisms occurring in anticipation of representations. There is reason to suspect that such anticipatory performativity is present. A burgeoning line of research has shown that individuals spend time prior to interaction constructing representations, such as in PowerPoint, with the goal of encouraging specific interpretations by their audience (Kaplan, 2011; Kellogg et al., 2006; Stark & Paravel, 2008). Barley, Leonardi, and Bailey (2012) showed how automobile engineers chose to include or exclude data from representations depending on their perceptions of whether future interactions with their audience would be contentious or congenial. By strategically designing their representations, engineers sought to shape how future interactions would unfold. Although these studies demonstrate that representations emerge outside of interaction, MacKenzie would likely still classify them as viewing representations acting as "cameras" of existing knowledge. These papers document anticipatory work devoted to representations but the practices they describe, such as including or excluding particular data from a chart, make no clear connection to influencing the broader process knowledge production.

To be considered an engine of social change, the anticipation of representation would have to shape work performances. I propose that, in this case, performativity would involve individuals shaping their own work practices not as a result of negotiations during previous interactions at knowledge boundaries, but in anticipation of future representational needs. If present, such effects would demonstrate that representations play a more active role in work than simply as conduits for knowledge transfer. Although our existing studies show that people make representations of their work, evidence of anticipatory performativity would suggest that those people make their work for representation. Among its implications, this type of finding would show that communicative mechanisms at knowledge boundaries can influence work even in contexts where interactions ultimately "fail" to bridge those boundaries.

Pollock's (2012) study of work at an IT Analysis Firm offers a preliminary example of how anticipating external representations might shape disciplinary work. The firm had gained popularity for a representation called the “Magic Quadrant” that compared service vendors in specific market sectors (e.g. operating systems, ERP software). Rather than studying how the representation affected client’s work, Pollack examined how the need to produce this representation influenced the way that analysts viewed the market. Analysts knew their representation would appear “cluttered” and become difficult for clients to interpret if it displayed a sector containing more than 25 vendors (pp. 102-103). Analysts excluded vendors from their analyses and segmented previously existing sectors into sub-components simply so they could produce a “beautiful picture” containing the “right” amount of dots (p. 104). The anticipation of the representation not only shaped analysts’ work practices, but led them to perceive their industry in new ways before any representation was produced. Although Pollack’s study offers preliminary evidence of anticipatory performativity in action, there is much room for development in this space. His account primarily documents how representation changed practices while offering little explanation of the mechanisms leading to these changes or why they were required in the first place. Part of this limitation arises because Pollack studied only one representation, in one relational context. Examining similar processes across a variety of relationships and representations would likely reveal a deeper understanding of the anticipatory process.

Adopting a performative perspective we see that current studies show people building representations of existing work without recognizing that the effort involved in producing those representations may have shaped how people accomplished that work. To understand the role of representations at knowledge boundaries fully, we must take an analytic approach examining work occurring in anticipation of a representation’s production. This paper seeks to identify and understand anticipatory processes surrounding representations and their effects on work by asking two related research questions: (1) How does the preparation of representations for use at knowledge boundaries shape work within a knowledge community? (2) What are some emergent consequences of this shaping for ongoing work practices?

Method

I spent a year following the work of four research teams at the National Center for Atmospheric Research (NCAR) developing applied numerical weather prediction (NWP) systems in partnership with outside organizations. NCAR is a nationally funded research center whose mission is to advance knowledge of the Atmospheric Sciences. NWP is the practice of creating dynamical weather forecasts using numerical methods (Halitner & Williams, 1980). A NWP model is a computer program that uses current and historical weather observations alongside algorithms simulating atmospheric physics to forecast future weather conditions. Applied models produce forecasts tailored to inform decisions in specific operational contexts. Applied weather modeling was an ideal context for this study because it was characterized by prominent knowledge boundaries and by the frequent use of representations to bridge those boundaries.

Comprised of atmospheric scientists and software engineers, each participating research team had contractual partnerships with organizations outside of NCAR to build applied systems aiding their decision-making: The Energy Team developed systems to help energy providers take advantage of wind and solar resources. This team consisted of four scientists, and five software engineers. They were working with EnergyCo, a service provider, to develop a system to predict energy production at wind farms. The team had already created a system that EnergyCo employees used in daily operations of wind farms and was currently working to improve that system.

The Range Team developed systems to facilitate test planning and execution at the Range Operations Command, an organization that operated several military test ranges. The core members this team included three scientists, four software engineers, a hardware specialist, and a range liaison. The relationship with the Range Operations Command was one of the longest standing applied partnerships at NCAR. Each range was geographically distinct (varying from arctic to desert) and tested different equipment (e.g. vehicles, explosives, missiles, etc.), which meant they each had unique and continually shifting forecast requirements.

The Dispersion Team specialized in simulating how chemical and biological agents moved throughout the atmosphere. They developed models with extremely high resolution, in some cases resolving the atmosphere at a granularity only feasible due to recent increases in computational capabilities. The team had developed new modeling techniques offering marked increases in accuracy over existing dispersion models. Its core membership consisted of five atmospheric scientists and two engineers. They were currently working with chemical sensor developers and using models to test virtual sensors to decide which technologies should be developed further.

The Antarctic Team created a system tuned to inform daily field operations at stations located in Polar Regions. With a core membership of two atmospheric scientists, this team was the smallest in the study. These scientists worked closely with another scientific laboratory, Polar Lab, and the government organization in charge of field operations in the Antarctic. Their primary work efforts involved the ongoing development and maintenance of a system that produced weather forecasts tailored for the Antarctic region.

One implication of these teams' applied work arrangements was that they each experienced the most severe form of Carlile's (2004) knowledge boundaries: pragmatic boundaries. Applied researchers routinely navigated the boundaries separating their own community (NWP and atmospheric science) from their partners' (energy providing, military defense, sensor development, and Antarctic operations). Applied partners came from starkly differing backgrounds, ranging from business strategists, to economists, to military commanders. Others were meteorologists. Although meteorology and atmospheric science share an interest in the weather, prior work has demonstrated these occupations involve distinct knowledge, practices, and objectives (Daipha, 2012; Fine, 2007). My participants reified this difference by repeatedly referring to meteorology as the "art" of crafting a specific weather forecast, and atmospheric science as the "science" of understanding general dynamics of the atmosphere.

The pragmatic nature of the knowledge boundaries on these teams was most visible in partners' disinterest in developing familiarity with researchers' scientific knowledge. The teams in this study differed from clearly collaborative relationships in other studies (e.g. Bechky, 2003b; Majchrzak et al., 2011; Nicolini et al., 2012), in that strong tensions existed between researchers' desire to perform science, their desire to collaborate, and the need to supply outputs to their partners. NCAR and their partners had markedly different motives for participating in their relationships: To researchers applied partnership offered the funds and resources necessary to accomplish science by developing novel simulation technologies. Researchers were mostly disinterested in the applications their models supported and resisted participating in their day-to-day operation and maintenance once they were complete. NCAR's partners were driven by an inverted set of motives. To them, weather models provided value for their application for operational decisions, not scientific novelty. Given these tensions, maintaining partnerships successfully depended on researchers taking measures to make their scientific knowledge commensurate with their partners' applied knowledge. Researchers' spent a significant amount of time producing representations to help them accomplish this goal.

Data Collection

I was a full-time observer at NCAR from September 2011 to August 2012, spending 40 hours each week on site at a research facility in Colorado, USA. Using semi-structured interviews and work observations, I captured a detailed record of teams' work activities inside and out of interactions with their partners. Being co-located with participants often facilitated happenstance interactions that led to informal conversations (e.g. at lunch time, or after-work refreshments) and impromptu data-collection opportunities (e.g. invitations to meetings or presentations).

My semi-structured interviews each lasted about one hour and were recorded for later transcription. My interview guide, which I updated as fieldwork and analysis proceeded, asked participants to describe their relationships with individuals both inside and out of NCAR: how partnerships formed and the communication involved in sustaining those relations over time. These interviews served several purposes. At first, they helped me develop a basic understanding of the science of weather modeling. Second, they allowed me to capture background information about the history, structure, and activities of each team. Third, they uncovered some of the specifics of applied research activities. In total, I performed 26 semi-structured interviews.

I also performed 42 work observations to capture a longitudinal narrative of activity on each team throughout my time in the field. Each observation lasted an average of three hours. I performed observations at different times of day, and days of the week. As part of my sampling strategy, I observed individuals in all occupational roles on each team (e.g. scientist, software engineer), many of them on multiple occasions. I also sought to be included in any episode when my participants interacted with their cross-boundary partners (e.g. meetings, teleconferences, program reviews). During observations, I asked my participants to perform their work activities as normal. I took detailed notes about my participants' interactions with people and technologies and, when possible, audio recorded all conversation for later transcription. When they worked alone, I asked participants to provide a running monologue of their actions. I collected copies of all relevant documents and frequently asked them share computer screen-shots of their work in progress. After each observation, I integrated audio transcripts with my fieldnotes and artifacts to create a database for analysis.

Analysis

I analyzed my data using iterative techniques based in grounded theory (Glaser, 1978; Strauss & Corbin, 1998), and proceeded with a two phase strategy: the first phase explored researchers' concepts of what their representations of model outputs would need to do in future cross-boundary interactions. The second phase used the findings of the first round of analysis as a lens to explore if the anticipation of representations led researchers to shape how they performed their own work. If researchers shaped their work practices in anticipation of representational needs, it would constitute evidence of anticipatory performativity in action.

My first step of analysis involved open coding to understand the role data representations played in the process of producing applied NWP systems. I identified of two distinct technologies that researchers' believed were important to producing an effective system: NWP models and data representations. Researchers viewed NWP models as central to their scientific activity and data representations as tools that served to communicate model outputs across knowledge boundaries. Researchers characterized data representations as distinct but highly interrelated with the NWP models whose data they displayed. Driven by researchers' acknowledgement of their de-coupled but interdependent nature, I isolated all references to each technology.

Next, I selectively coded all references to data representations for mention of qualities that researchers perceived as important to facilitating their role in sharing knowledge across boundaries. I did not attempt to gauge the data representations' actual success or failure in cross-boundary interactions. Rather, I sought to uncover whether researchers possessed shared expectations about the required nature of their future representations. Evidence of such expectations would suggest researchers anticipated representational requirements in the time before they sought to build those representations. If these expectations were shared across individuals and teams they would constitute one way that representations might produce performative influence on prior work practices. My analysis here not only revealed shared representational requirements, but that researchers acknowledged making explicit efforts to fulfill these requirements. The result was the identification of a class of work that researchers performed within knowledge boundaries in anticipation of communicating with cross-boundary partners in future interactions. I labeled this type of work anticipatory work because it involved strategically shaping models and their outputs to facilitate future representation to a particular cross-boundary audience. Next, I used constant comparison to group references to anticipatory work into themes and identified three representational requirements that researchers recurrently saw as important for representing knowledge to their partners: appropriate timeliness, perceived accuracy, and perceived usefulness.

Although my first phase of analysis revealed that researchers anticipated their representations, I still needed to explore whether the need to fulfill these requirements influenced how researchers performed their work. My second phase of analysis sought to understand whether representational requirements shaped how researchers built their NWP models. I selectively coded all instances where researchers talked about NWP models for mentions of the three requirements. I paid particular attention for instances where scientists invoked requirements when deciding how they should go about building their weather models. Next, I engaged in constant comparison of these references to identify two distinct mechanisms by which representational requirements shaped modeling practices: influencing research questions, and shaping the modeling process. Having identified the performances associated with anticipatory efforts, my final phase of analysis stepped back from the micro level to examine the broader consequences that researchers perceived these efforts had upon their ability to produce knowledge. I addressed this by isolating researchers' explanations for why they believed such activities were necessary and how their work to fulfill requirements influenced their ongoing inquiry. These explanations triangulated my previous findings and offered examples of how micro-level adaptations of modeling work influenced the knowledge researchers produced within their own boundaries.

Findings

Researchers at NCAR spent the majority of their days outside of the types of cross-boundary interactions frequently examined in the literature on work at knowledge boundaries. They spent this time sitting at their computers doing activities such as developing new weather models, comparing their models' predictions with alternative models, fixing bugs in their computer code, and writing programs to render forecast data into visual representations. Researchers wrote reports, academic articles, and research proposals. They also frequently met among themselves to coordinate their modeling activities. The separation of researchers' and applied partners' work meant that NCAR's partners primarily interacted with NWP systems through data representations that the researchers had produced specifically for this purpose. This was what partners preferred. As an engineer on the energy team put it: “When they [our partners] look at our tools, they just want it to say what the weather is going to be and how it will affect their equipment. They don’t want to know how we came up with our guess; they just want our best guess. They don’t want a rationale.” NCAR’s partners were less interested in knowing how researchers produced forecasts than the implications that those forecasts held for their work. By carefully crafting data representations, researchers sought to bridge the gap between their own knowledge of weather modeling and their partners’ desire for information informing decisions in a specific applied context. Before going deeper into the process by which researchers produced such representations, it is worth discussing the technologies at play in this context.

NWP Models, Data Representations, and Anticipatory Work

Researchers distinguished two types of technology making up their applied NWP systems: NWP models and data representations. The first, NWP models, were computational tools that simulated the atmosphere to forecast future weather conditions. As a discipline, atmospheric science had long relied on numerical approaches to explore and understand atmospheric processes (Edwards, 2010; Harper, 2008; Nebeker, 1995). The following example illustrates how deeply this held at NCAR. In one observation, two researchers spent hours sitting at a computer debating how to use their NWP models to understand a pattern they had observed in their data. At one point, they paused to explain their current work activity:

> Say you’re trying to forecast the weather and you have a set of initial observational conditions for an area. We’ve found that if you correct the initial conditions on a mountain top, it has more positive impact on the forecast than if you make comparable corrections at lower altitudes. This implies that you should put more observation sites at higher altitudes because they’ll have more impact. But the question is: from a physical perspective, why is that happening? We’re talking through the theory. We’ve done some simple experiments with models and we’ve shown it happens with real world forecasts. We’re trying to get a paper published but we need a better explanation of why.

This representative excerpt illustrates three different roles that NWP models played in researchers’ work. First, researchers’ objectives often centered on improving their models’ accuracy and validity. If the pattern these scientists observed held to be true, it was interesting because it would help them produce more accurate weather models. Second, NWP models were the primary tool researchers used to make their discoveries: this pattern was only visible because the researchers had manipulated enough NWP models over time to uncover it.

Finally, models were important for demonstrating patterns to the broader scientific community. The researchers had created a constellation of model runs that reproduced the effect consistently enough that they felt it would convince reviewers at a scientific journal of the validity and importance of their finding. NWP models acted as epistemic objects of atmospheric science (Knorr-Cetina, 1999; Rheinberger, 1997; Vertesi, 2014) because they were both the mechanism and objective of scientific practice. As shown in previous studies of science and technology (e.g. Latour & Woolgar, 1979), the process of building NWP models at NCAR was tightly integrated with the production of scientific knowledge.

Although NWP models were central to scientific practice, researchers also recognized that model outputs of scientific interest (e.g. wind speed, temperature, and precipitation) were rarely directly applicable for their applied partners. Each team also developed a second set of technologies in their work which they characterized as paramount to facilitating the applied aspect of NWP: data representations. Darren, a scientist on the range team, differentiated data representations from their underlying NWP models:

> We have these output files from the model, but you can't just provide a forecaster a file on a disc and claim your job is done. So, given the forecasting they do, what other scripts do we write to organize the data to display it in a way that makes their job easier? You can communicate through the presentation of information and data, and we do that. The better the maps, data, and tables suit their purpose, the less a barrier for forecasters to understand the forecast the model produces.

Darren's team recognized they needed to build data representations that would help bridge the knowledge boundaries separating them from their applied partners. If NWP models were epistemic objects, researchers considered representations as playing a translational role that would facilitate communicating atmospheric knowledge across boundaries, more akin to the role of representations in the literature on boundary objects (Bechky, 2003a; Carlile, 2002). Darren's quote also reveals his understanding that building representations required work in addition to that required to build a suitable NWP model. Table 1 summarizes the technologies present in each team's work.

[Insert table 1 about here]

I use the term anticipatory work to describe the process by which scientists at NCAR anticipated their partners' representational needs and produced data representations that would meet those needs. Nikolas, manager of several research teams, described how this work distinguished his teams from others: "Weather scientists often just produce a product, put it on a webpage, and let the user figure out what to do. I call that throwing over the fence. I argue you need to really tailor things for specific applications. You need to extract what is really relevant so a user can put weather information in context." Nikolas viewed this work as a unique aspect of working at knowledge boundaries: if his team did not take anticipatory measures to tailor their representations, their partners would have difficulty appropriating the NWP system. Nikolas was not alone in this recognition. Scientists routinely discussed several types of representational requirements they needed to anticipate and meet if they wished to produce representations that would bridge the knowledge boundaries separating them from their applied partners. Three representational requirements emerged consistently in my analysis: scientists believed they needed to create representations partners would perceive as timely, accurate, and useful within their particular applied context.

Appropriate Timeliness. The first representational requirement involved managing practical differences between the timeframes of exploratory scientific process and applied partners' real-time decision-making. Peter, a dispersion scientist, demonstrated how the pace that partners needed access to knowledge varied depending on the practical aspects of the context where they sought to apply the representation:

> For some applications, they can't wait a day for an answer. So this is really your operational task, like emergency response. If fire, paramedics, and police are out there with a spilled tanker car, or a derailed train, they need to say "we need to evacuate people over here." Or, "you need to be this far down wind and you'll be okay." They need that answer in less than ten minutes… as soon as possible. Whereas, if you are doing test and evaluation, you have the luxury of bringing higher fidelity to your solution. And higher fidelity matters because of the increase in accuracy. Whereas for emergency response, you kind of actually just want to know that broad area, and that's good enough.

Representations needed to be available at a pace fitting the speed of partners' decisions and this requirement varied depending on the context where the representation would be used. The rapid nature of emergency response decisions necessitated representing forecast information as quickly as possible. The need for rapid delivery diminished when partners' applications were less urgent, such as when simulating the performance of potential weather sensors to see if they were worth investment.

The dispersion team's main project during this study was characterized by little need to produce representations rapidly: the researchers would represent their modeling work in the form of a research report consolidating the outputs of a large number of simulated sensor tests. This representation would help a sensor technology developer decide its long term investment strategy for developing capabilities in their technology. Because the decisions being made with the report would occur outside of a “real-time” context, dispersion researchers were free to adopt NWP techniques that were highly accurate but took months to compute. With other projects, however, the need for fast paced representation was more of a factor. In one extreme case, a researcher on the range team described how this representational requirement affected her work: “To do ‘nowcasting,’ or forecasting of what’s happening now, you need data now. You can’t wait three hours for it because by then, it’d be old news.” In this application, applied partners desired a representation that would support decisions in real-time. Meeting the requirements of appropriate timeliness here meant researchers’ systems needed to produce representations so quickly that even the data used to seed the weather model needed to be available in near real time. No matter how innovative this system was from a scientific perspective, if it took too long to produce representations, those representations would fail to meet their partners’ decision-making needs.

Perceived Accuracy. The second representational requirement emerged from the recognition that researchers’ concepts about what made a representation “accurate” often differed from their partners’ perceptions. By anticipating these differences and constructing representations to manage them, researchers believed they could bridge this boundary and reduce the possibility of partners’ rejecting their tools. The consequences of neglecting differing perceptions of accuracy came up one day when Rick, a manager at EnergyCo, described how he came to view NCAR’s wind energy system as accurate enough for use in choosing to reduce power production at their coal plants. He attributed this trust largely to the accuracy of a representational feature called the “look back” mechanism which compared forecasted energy production to past observations of a farm’s actual production: “We could see how the forecast was doing and people just got increasingly comfortable with it. On the other hand, if there was a disconnect between the observation and the forecast, that disheartened people.” Figure 1a illustrates this mechanism. Note how in this example recent forecast data has “disconnected” from observations.

[INSTERT FIGURE 1 ABOUT HERE]

From the scientists’ perspective, the “disconnect” in Figure 1a offered valuable knowledge because it accurately characterized the NWP model underlying the representation. The researchers could use a discrepancy between forecast and observation to identify places where they might need to improve their model. However, EnergyCo was less interested in improving the model's accuracy than having access to the most accurate prediction of energy production possible. To them, the disconnect signified that the model was inaccurate and unsuitable for informing their decisions. As Rick put it,

> "That disconnect creates a lot of consternation because you're expecting the forecast to be bound in reality. And this is reality [pointing to the observation line]. The past is reality, we know what it is. So, when you take a step into forecast space it had better be bound in reality. It doesn't matter if you can explain why the disconnect is there, and all the smarts that go into the forecast line, because it's obviously wrong. If all of the best science does that [pointing to the disconnect], then the science sucks! You should be doing something different."

Representing the disconnect fostered perceptions of inaccuracy at EnergyCo which led to rejection of the system's utility for decision-making. Meeting EnergyCo's desire for perceived accuracy required that scientists anticipate these reactions and shape their representation accordingly. To this end, the team drew on a technique called forward error correction that continually adjusted the system's forecast to look more like past observations. Figure 1b illustrates this change, showing how the error corrected prediction minimized the difference between the NWP model and previous observations, displaying data that would appear accurate from EnergyCo's perspective. Suggesting that this action helped build a representation that bridged the knowledge boundary, Rick cited this modification as key to incorporating the model in their daily routines.

Perceived Usefulness. Finally, researchers recognized representations needed to display output that would readily integrate with their partners' knowledge. In most cases, partners' required outputs differing from standard NWP model outputs. The energy team discovered that providing predictions of wind speed (an output of scientific interest) was much less useful to EnergyCo than a representation displaying predicted turbine energy output. By displaying outputs coupled to partners' knowledge, scientists sought to minimize the translation necessary for partners' to use representations to inform their practice. Andy, a scientist on the Antarctic Team, illustrated this requirement when recounting a recent trip to Antarctica, where he discovered a type of output forecasters needed that was not currently represented by their system:

> I got a good feel for the weather down there. What it meant when they said, "The model doesn't handle blowing snow. Is there any way you can get blowing snow in the display?" You can look out

> the window and see. Blowing snow can completely shut down operations at an airfield. You get snow drifting up to 20 meters deep that can completely obscure the ground. So anybody trying to land will have to turn around and go back to New Zealand. We don't represent blowing snow in our model. Forecasters have to use the observations, the model wind fields, and the model precipitation fields, to decide if blowing snow will be a problem.

Antarctic field operations relied heavily on forecasters' ability to accurately predict dangerous conditions such as the development of snow drifts that could cover a runway. NCAR's representation, however, only displayed predictions of where snow would fall and how strong winds would be – not the presence of snow drifts. To forecast blowing snow, forecasters needed to do extra work to compare their own observations with NCAR's representation so they could translate its outputs into a format suitable for their work. Andy recognized that if he could create a representation that directly displayed blowing snow, he could minimize this estimation work. Accomplishing this requirement, however, was no simple task. Andy later explained that writing the code for a blowing snow forecast would involve new physical equations that were currently absent from his NWP model.

Anticipatory Effects on Modeling Practice

For anticipatory work to qualify as having performative influence, researchers would have had to shape how they performed their own disciplinary practices (i.e. the process by which they built their NWP models) as they sought to anticipate and meet representational requirements. Initial evidence of this was present in the preceding sections: each example tied the steps necessary to meet representational requirements with the design of the NWP model underlying those representations. I next sought to explore how prevalent these performative influences were in my data. Using the three representational requirements as an analytic lens, I discovered that team members frequently invoked future representations as an important factor when deciding how to build the models they considered so central to their scientific activity. Specifically, representational requirements influenced modeling practice through two different mechanisms. First, they influenced what researchers focused on by informing which research questions they could address. Second, they influenced how researchers built their models by informing their choices during the modeling process. Table 2 provides examples of how each requirement influenced modeling work on the research teams. As the table indicates, there were fewer specific cases of anticipatory influence on research questions in the data than instances of influence on the modeling process. This difference in prevalence likely emerged because researchers spent a much larger portion their time building models than choosing which phenomena they should study.

[INSERT TABLE 2 HERE]

Influencing Research Questions. Researchers characterized applied partnerships as beneficial for their research because they offered the resources, such as unique data, computational resources, and financing, necessary to explore historically understudied topics. Given all of this novelty, potentially interesting research topics frequently emerged during the model building process. Representational requirements, however, limited researchers' ability to pursue questions as they came up. As a range scientist described:

> In applied work, there are often competing goals. If the sponsor wants an end result that is not, in itself, scientific, it can be a limitation. An extreme example would be if they wanted an engineered system that made their jobs easier but they wouldn't pay for us to go to any conferences to talk about it. That's not the kind of work we like for long term satisfaction. NCAR is a research institution. A strong component of everything we do is sharing scientific ideas among other scientists. Presenting work in open forums, conferences, journal articles, you know.

The need to represent research outputs to applied partners influenced the phenomena researchers could explore in their work. Another scientist captured this when by saying that some research questions were "of scientific interest, but not of customer interest." This sentiment was supported by an EnergyCo manager: "If there is one thing I've groaned about during this project it's that I have to be very specific with deliverables. You know, 'that's great research and I'm very interested, but it drives to what?' We're not going to just explore this to explore it. We need explore it with an end in mind." Researchers faced pushback if they could not frame the research questions they wanted to pursue as having potential to produce applicable representations.

One example of such an effect occurred on the Range Team. Researchers on the team had become interested in developing a NWP system capable of producing real-time forecasts of wind speed, icing, and turbulence at a much finer scale than existing models permitted. The scientists believed this effort not only aligned with their interest in increasing model fidelity, but that they could anticipate using this model to produce representations informing the operation of unmanned aerial vehicles (UAVs). Even so, Darren's team found itself putting off this work. He explained why:

> One of the costs of collaborating with the ranges is that they may want us to put off a line of inquiry until later or potentially forever. I would like to take some of the people in the lab who work on

> turbulence, icing, visibility, and begin to apply it to UAV scale of weather. Their sensitivity to these factors is quite different from a commercial aircraft. I see a real opportunity because there's going to be a growing use. Our lab could be out on the cutting edge of doing the weather support for that, but the director of the ranges doesn't feel it's a good use of their money right now.

Even though Darren believed this research could be used to produce representations that would benefit the ranges, his opinion was not enough to move forward. They had to delay this work because the range director did not view these potential representations as producing useful knowledge: although the test ranges had been seeing an increased prevalence of UAV testing, the range director did not perceive enough demand to consider this potential system useful enough to embark on a new project. In cases like this, representation requirements led to performative influence on researchers' work. Although NCAR could produce such a set of representations, their partners controlled the purse strings and access to the data that could facilitate that system's construction. This division of resources required that partners perceive any activity the team pursued as being mutually beneficial – a quality only achieved by performing research that produced representations meeting the ranges' requirements. Otherwise, researchers had to abandon their ideas.

Shaping Modeling Practice. Further evidence of anticipatory performativity was visible as researchers decided how to build their NWP models. A hint of this was visible in Peter's discussion of how the Dispersion team built models differently depending on their partners' needs for accuracy and timeliness: when timeliness was less a factor, scientists could develop fine grained models that took longer to process but more faithfully simulated the atmosphere. When speed was necessary, teams were forced to use simpler algorithms to reduce computation time. The nature of the model, then, shifted in anticipation of the future representations it needed to produce.

Such considerations featured prominently one afternoon when Pam, Kris, and James, three scientists on the Energy Team, met in James' office to discuss a new system that would find patterns in multiyear dataset of weather observations to inform choices about where to build solar and wind farms. They were deciding between two algorithms for identifying patterns in the data: self-organizing maps, and principal component analysis. Self-organizing maps is machine learning technique that processes large datasets into piles based on similarity. This technique was unique because it organized data in a manner that easily supported visualization.

James had used self-organizing maps before but Pam and Kris were unfamiliar with the technique. Principal components analysis processes a dataset as a whole and outputs a series of vectors, called principal components, each explaining a unique portion of the dataset's variance. Principal components were commonly used in atmospheric science and all three scientists had used them previously. Because Pam and Kris were unfamiliar with self-organizing maps, James started the meeting by briefing them on the method. The following excerpt captures the shift in discussion from self-organizing maps' technical details to its representational potential:

> James: Once you use the mapping technique to generate the initial patterns you can use a secondary clustering method to reduce the groupings into a subset of unique patterns.
>
> Kris: Okay. I know that with PCA you can restrict the number of principal components to do a similar measure. With this analysis, do you have to re-compute the whole thing?
>
> James: No, it hasn't been recomputed. I'm using a hierarchical clustering scheme and I'll explain why. [Pam jots something on the notepad in her lap.] What's really nice is, my previous client sometimes had quite a bit of time to do their analyses and sometimes they didn't. With this method I can say "there are 6 unique patterns." And they can go "Great, we have time to do all six" or "no, I only have time to do three. Which three should I look at?" Well, I can go back up the hierarchy and say these three. So "That's how much time you have? These are the groups you should look at."
>
> Pam: Oh, that's really cool!
>
> Kris: This is good! Compared to principle components where you add additional information. Here you can just aggregate upwards.
>
> James: Right. Principal components are really nice for looking at what is contributing to the variance. When you're dealing with people outside of the field, though, that is a very abstract concept and they look at a field and they're going "well my data don't really look like this. How do I use this?" Whereas with SOMs, it's not clear how much of the total variance each of the patterns is explaining, but they know it's frequency of occurrence and they can see in their data: yes this is a pattern that occurs. They're very comfortable.
>
> Kris: Right, any one of those categories is a pattern that does occur. Whereas the second principal component is just something mathematic.

Although James admitted principal components were superior for explaining patterns in the data, he found that self-organizing maps facilitated representations that would be perceived as timely and useful to an applied audience. For example, the self-organizing maps algorithm allowed James to adjust the number of patterns the system identified rapidly to accommodate for the shifting his partners' shifting time constraints. Herein lay the distinction researchers' identified between the two methods: Principal component analysis was an elegant analytic technique that explained the variance in a dataset, but was weak in its ability to represent information in a timely and useful manner. Self-organizing maps were weak at explaining the patterns they revealed but produced outputs could easily meet representational requirements. This potential for meeting representational requirements informed the teams' decision. A few minutes later, Pam suggested they choose the method best suited to their partners' needs, closing the decision-making by saying: "I'm sold on self-organizing maps at this point. This is a great idea. Lots of great science!" The shape of the model they used to perform that science, however, was influenced by their anticipation of partners' representational requirements.

Anticipatory Performativity and Scientific Knowledge

At NCAR, NWP models were intimately tied with researchers' ability to produce scientific knowledge. This final section demonstrates how the performative shifts identified in the previous section combined to engender influences on researchers' ability to produce their own knowledge. I will do so by outlining two cases from my data illustrating the influence that anticipatory work had upon the scientific knowledge that researchers produced in their work activities. The cases show how efforts to facilitate future representations led scientists to refrain from appropriating resources, to explore new types of weather phenomena, and in one case to abandon a fundamental scientific discovery.

The first example demonstrates how anticipatory work led the Antarctic Team to decide not to appropriate a new computing resource to its fullest potential. The team's model and representation required significant computational resources: the version operating in 2011-12 ran on a dedicated set of 96 nodes (332 processors) on NCAR's supercomputer. The system ran twice daily, initialized with data available at 0z and 12z, creating forecasts for the following 120 hours. This computation took between four and six hours, at which point representations became available to forecasters in the Antarctic. Andy described how forecasters' need for appropriate timeliness influenced his team's resource usage: "They're interested in Antarctic weather in a much more specific way than us. For them it comes down to lives; being able to get people safely here and there. We just see Antarctica as an interesting case study. Aside from keeping the system running, we don't care if the data we're studying is available in real-time. But that is an absolute necessity for forecasters, which makes it a necessity for me." For his research, Andy was more concerned with the fidelity and novelty of the model than the time it took to compute. The primary reason the team used such extensive resources to operate their system was to meet their partners' requirement for timely representations.

In 2011, NCAR was in the final phase of installing a new supercomputer that would come online in Summer 2012 that would give the team a fifteen fold increase in their computational resources (from 96 to 1344 dedicated nodes). A major thread of discussion throughout the year was how the team would use of these resources once they became available. During one observation, Andy outlined his teams' options: First, they could speed up the current system to provide forecasters access to representations in under an hour. Second, they could increase the fidelity of their NWP model, which would increase the resources required for each run but also increase forecast accuracy. Finally, the team could use the new computer to test and develop new NWP modeling techniques. The first option was feasible from the moment the computer came online. The second and third would take years to implement. Andy described his team's rationale:

> We need to sit with this machine for the next five years. If we run our forecast model way too fast initially, we don't want the forecasters to get used to that. Basically, for all of the system's history, it's taken 4-6 hours to run the model. The forecasters are used to that and know when to expect the forecast. If we suddenly run that model in half an hour, or one hour, they'll complain if it starts taking longer. If things slow down because we want to put higher resolution in, or the more complex schemes they'll say: "Hey, you used to give us the model in half an hour, and now it's taking an hour and a half. What's the deal?" There's the human impact I guess.

It was technically feasible for the team to use the resources to speed up the system initially and then slow it down gradually as they needed those resources to add complexity to their model. However, opting for such a strategy would ignore its influence on partners' concepts of appropriate timeliness. Offering representations more quickly would please the forecasters, but would also lead them to attune to this pace of delivery and resist any future changes that slowed representational availability. This strategy would leave no slack resources the team could use to develop their model, and thus, to produce new scientific knowledge. To balance timeliness requirements with a desire to perform science, the team adopted a computing strategy that left significant resources unused during early phases of the new computer's availability. The result was a compromise where forecasters saw no change in timeliness and researchers put off their desire for scientific achievement.

A second example illustrates how pressures to produce useful, accurate, and timely representations led the Energy Team to discover and then to abandon a fundamental flaw in their simulated physics. When the team first set out to build a system representing turbine energy outputs, they realized their simulation model would need to accurately predict winds at turbine heights. This was challenging because most models in the weather community were tuned to predict either large scale weather or detailed conditions at the planet surface. Wind turbines are located between 70 and 100 meters from the ground which places them at the upper edge of the lowest layer of the atmosphere: the planetary boundary layer. Sorin, a boundary layer specialist, explained how this representational requirement drove the object of his modeling research: “There are a number of parameterizations of the boundary layer and we initially didn’t know which one predicted wind at rotor height the best. Because power is related to wind-velocity cubed, any little error in prediction results in a large error on power prediction. So it’s really important to get wind speed as accurate as possible.” Driven by their partners’ requirement for accurate power predictions, Sorin found himself exploring how models performed in an underexplored part of the atmosphere. After testing the available modeling options, Sorin made an interesting discovery: “All the parameterizations predicted wind speeds that were a few meters per second lower than observations. They were all under-predicting! So that led me to think there is something fundamentally off with the parameterizations.” Driven by the desire to represent useful outputs (energy instead of wind velocity), and the need to make his wind forecast particularly accurate (because $E \propto V^3$), Sorin discovered a bias that was consistent across all of the boundary layer simulations available to the scientific community – anticipatory work led to the production of novel scientific knowledge.

These performative influences continued as Sorin realized that timeliness was also a requirement: even with a systematic bias, the team still needed to create a functional system that produced operational representations within the agreed upon timeframe. Sorin explained how this need stymied his research:

> Unfortunately, we knew we had to deliver an operational system to the user so we could not explore things further. Although we’re an applied lab, we often identify fundamental problems. Sometimes, if it is a short project, we can pursue them. Other times we just have to communicate our findings with people who are committed to fundamental research because they have that luxury because they are base funded and that’s part of their mission.

Given the teams’ need to produce representations for EnergyCo, Sorin had to abandon his desire to explore the problem he had uncovered in the model. His quote reveals that he conceptualized this as a broader influence that the need to perform anticipatory work had upon his ability to pursue scientific knowledge: although he often found himself positioned to uncover questions that were relevant to basic science, he found that anticipatory work limited the scope of the research his team could pursue.

Discussion

This study makes two primary theoretical contributions, the first being the introduction and demonstration of the value of using a performative lens when studying knowledge representations at knowledge boundaries. As argued in the introduction, a performative lens conceptualizes representational objects as entangled with disciplinary practices at a much deeper level than previous studies of cross-boundary work have acknowledged. At NCAR representations themselves became a central focus of work practices within a knowledge boundary. The results showed that researchers' desire to produce representations to facilitate communication influenced researchers' own knowledge producing activities. Having identified these influences on researchers' work, the findings produce a number of implications for research on data representations, cross-boundary communication, and cross-functional teams in organizational contexts.

The second theoretical contribution was the extension of previous theorizing on performativity by developing the concept of anticipatory performativity, the notion that the anticipation of a representation can engender influences on disciplinary work. Figure 2 illustrates three different views of performativity. Each panel demonstrates a different theorized relationship between a representations' characterization of the world and disciplinary work practices. The first panel illustrates the standard account where representations are direct reflections of existing disciplinary practices. In this view, representations function by making practices and knowledge visible but any change in practice that occur result from negotiations surrounding them, not the object itself. The second panel demonstrates performativity in the sense of MacKenzie (2006) where a representation not only demonstrates a particular vision of the world but, by making that vision tangible, directly affects how people go about their work. In this form, representations influence action, but that influence still occurs after the representation is introduced into use. Finally, in the case of anticipatory performativity, work practices are shaped prior to representation so they can produce the types of knowledge needed for future communication.

[Insert Figure 2 Here]

Demonstrating anticipatory performativity at NCAR raises a number of implications for how we conceptualize data representations at knowledge boundaries. First, uncovering anticipatory work challenges current explanations of how representations operate. Instead of viewing representations as passive mediators that make existing knowledge accessible, the findings from NCAR show that the objects we often examine in interactions result from a processes whereby experts shape their own work practices to produce outputs that can bridge boundaries. Recognizing that anticipatory performance is at play problematizes the locus of influence in our theories of representation. By studying representations during interaction, we often attribute any effects on communication to the qualities of objects themselves. If we recognize that these representations may have engendered anticipatory work, however, the influence of that representation becomes less situated in the object itself and more entangled with how individuals modified their disciplinary work so they could produce outputs that would be representable.

This calls into question how we might interpret findings of previous research on representations at knowledge boundaries. For example, Carlile (2004, p. 564) argued that 3D models allowed engineers to "first represent their various concerns, data points, and requirements, then engage each other to identify, negotiate, transform, and verify the knowledge that they would then use to design the vehicle." While a performative approach would not reject this explanation, it would suggest that it overlooks and important part of the process: part of the 3D models' success in facilitating knowledge transfer may have arose because the engineers who built the model modified their designs beforehand so it would be more representable. A performative perspective on representations, then, aligns more closely with recent socio-material accounts of technology in organizations which posit that a technology's role is often tied to the social context in which it is produced and interpreted (e.g. Leonardi, 2013; Orlikowski, 2007).

The case of NCAR also informs our understanding of the dynamic role that representations play in ongoing work practices. Nicolini, Mengis, and Swan (2012) argued that objects play multiple roles at knowledge boundaries. This study suggests that interesting consequences may emerge when the same object needs to perform multiple roles. At NCAR, NWP systems were simultaneously epistemic objects that were the source of and subject of researchers scientific inquiry (Knorr-Cetina, 1999; Rheinberger, 1997), and potential boundary objects designed to facilitate communication across knowledge boundaries (Fujimura, 1992; Star & Greisemer, 1989). Researchers' anticipation that their representations needed to function as boundary objects influenced their role as epistemic objects. They went to great lengths, to produce objects that would be communicable, but in doing so experienced a trade-off in their ability to use those objects to produce their own forms of knowledge. This opens an interesting venue for future research exploring how context and materiality influence an objects' potential for performing multiple roles at a knowledge boundary.

My analysis strategy prevented me from assessing if anticipatory work increased the efficacy of representations at knowledge boundaries, but this is clearly another important topic for future exploration. There may be important differences in the operation of consciously constructed representations, such as the ones described at NCAR, and representations that emerge naturally as interactions unfold, such as the ad hoc appropriation of physical objects in the environment (e.g. the turbo pump fixture in Bechky, 2003b, p. 322). One might expect the constructed representations that NCAR created to more readily afford cross-boundary manipulation than "raw" objects drawn from the surrounding environment. Further, future research should examine the practices by which individuals construct understandings about their partners' representational requirements. Scientists at NCAR frequently spoke about how understanding their partners' work was important to successfully developing representations. Representational success may rely heavily on accurately understanding partners' values and knowing how to shape ones work to satisfy those values.

NCAR researchers conceived of three types of representational requirements: appropriate timeliness, perceived accuracy, and perceived usefulness. The specific interpretation of each requirement varied across relationships and applications. Given their contingent nature, these categories are likely neither exhaustive nor generalizable to every knowledge-diverse work context. The broader point, that knowledge boundaries engender representational requirements is more likely to generalize. Another venue for exploration, then, would be to understand the processes by which individuals manage tensions among the representational requirements they encounter. For example, researchers often characterized timeliness and accuracy as existing in opposition: performative adaptations associated with quicker presentations often came at the cost of reduced representational fidelity. One reason teams at NCAR were able to negotiate these tensions so effectively in their work was that they were building representations for very specific audiences (e.g. one group of forecasters at one particular applied organization). There are, of course, many contexts where the diversity of actors at a knowledge boundary is greater. In Kellogg, Orlikowski, and Yates' (2006) study, for example, participants needed to build representations that could simultaneously be interpreted by other units in their organization, their management, and their clients. One would imagine that as the number of groups involved in a particular cross-boundary work arrangement increased, the diversity of representational requirements would present workers with an exponentially more difficult problem: how does one anticipate and accommodate for multiple audiences simultaneously? Are there circumstances where these requirements are so irreconcilable that they prevent representation from occurring?

More broadly, the case at NCAR demonstrates the value of shifting from a perspective that views communication primarily as a mechanism of information and knowledge transfer to a more performative stance on communication at knowledge boundaries. Although it still recognizes that the ultimate goal of communicating at knowledge boundaries may be sharing and manipulating knowledge during interaction, a performative approach posits that the challenges of communicating across boundaries can, in themselves, engender meaningful consequences for work. In this view, communication shifts from being an episodic occurrence, to a longitudinal process that drives individual activity. By uncovering anticipatory work, this study demonstrates that cross-boundary communication involves more work than simply transferring, translating, or transforming knowledge during interactions (Carlile, 2002, 2004). Each representational requirement was addressed outside of interaction, but mapped onto Carlile's framework for communicating at pragmatic knowledge boundaries: By addressing timeliness, researchers sought to address practical differences between scientists and applied partners' knowledge; considering accuracy facilitated communication addressing semantic differences dividing partners from one another; Producing useful outputs translated scientific information into a format that aligned with partners' knowledge and practice.

This study expands our understanding of how working across knowledge boundaries can influence the knowledge produced within them. Taking a performative perspective at NCAR revealed a more dynamic account of knowledge where a community modified its own practices because it was located at a boundary. It is important to note that the anticipatory influences on researchers work were not always constraining: the energy team did discover a hereto unidentified flaw in their models, the Antarctic team did corral access to new computing resources, and the range team did identify research questions that offered potential for scientific contribution. Anticipatory performativity could also exhibit itself through inaction, as demonstrated by researchers refraining from asking particular questions or postponing their resource usage. Another important implication then is that knowledge boundaries can shape community action regardless of whether or not they are “successfully” bridged. The teams in this study went to great lengths to facilitate their representations. The Antarctic Team, for example, travelled half-way around the globe to understand their partners’ representational requirements. We should be mindful of these potential consequences when we tout the value of interdisciplinary teams in modern organizational contexts. When managers encourage specialized sub-units to interact, they may not recognize that efforts involved in approaching those interactions might lead to unintended consequences for those unit’s work practices.

Power dynamics are another area requiring further attention as we explore anticipatory work at knowledge boundaries. Researchers at NCAR were highly dependent upon their applied partners to accomplish their work, which was driving force behind the findings herein: if researchers could not satisfy their partners with representations, they risked losing support for their research. As described in the methods section, this dynamic served this study by making representations and their work visible for analysis. One might expect that levels of anticipatory work might vary in other settings such as clear collaborative relationships, or contexts where the producer is in a position of power over their partners.

Finally, we would do well to examine how the ongoing engagement in cross-boundary work influences disciplinary practices over longer periods of time. The consequences discovered herein were only enacted during a single relationship. If anticipatory work led researchers to avoid particular questions and focus attention on new aspects of their environments, we might expect longer term effects to arise outside of a single relationship. For example, researchers frequently spoke about how their ability to secure future applied partnerships was influenced by the work they had performed in previous ones. If this is the case, then organizational scholars would definitely do well to examine the processes by which local transformations of work practice at knowledge boundaries endure over time and the implications these shifts have for disciplinary identities.

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Table 1
Overview of applied NWP systems in this study

System	NWP Models	Data Representations
Range	- multiple NWP models (tuned for each range) - short-term prediction system	- web portal with displays tuned for each range's needs (e.g. local forecasts, lighting prediction, runway conditions, etc.)
Energy	- NWP model (tuned for turbine height winds) - turbine model	- Java based display showing real-time forecasts of energy production at wind farms
Antarctic	- NWP model (tuned for polar weather)	- dynamically updated web page with multiple data plots
Dispersion	- NWP model (tuned for high resolution of surface winds) - proprietary dispersion model	- graphical plots - PowerPoint presentations - written reports

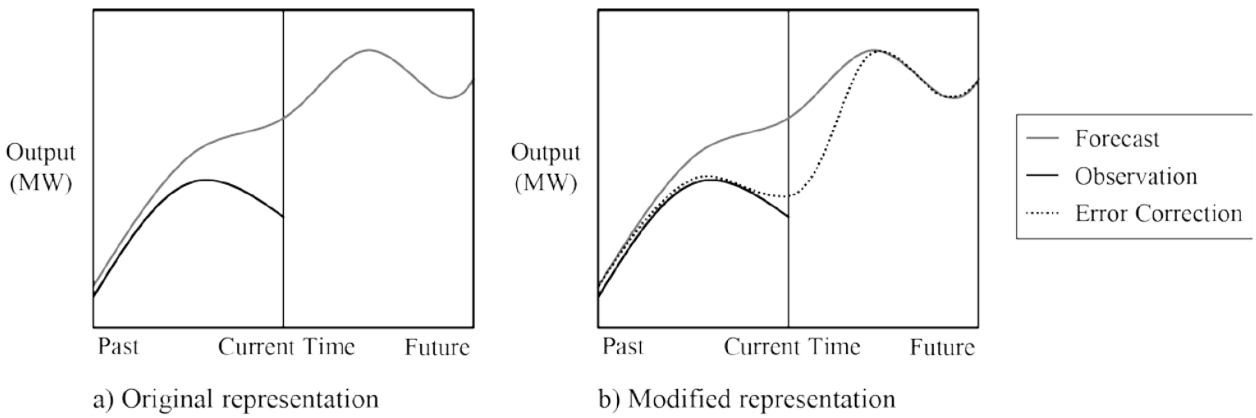

Figure 1. Two examples of data representations produced by the energy team (reconstructed from fieldnotes). Panel (a) shows the original display with "look back" mechanism and "disconnect". Panel (b) includes the error corrected line that adjusts forecast values to more closely match previous observations.

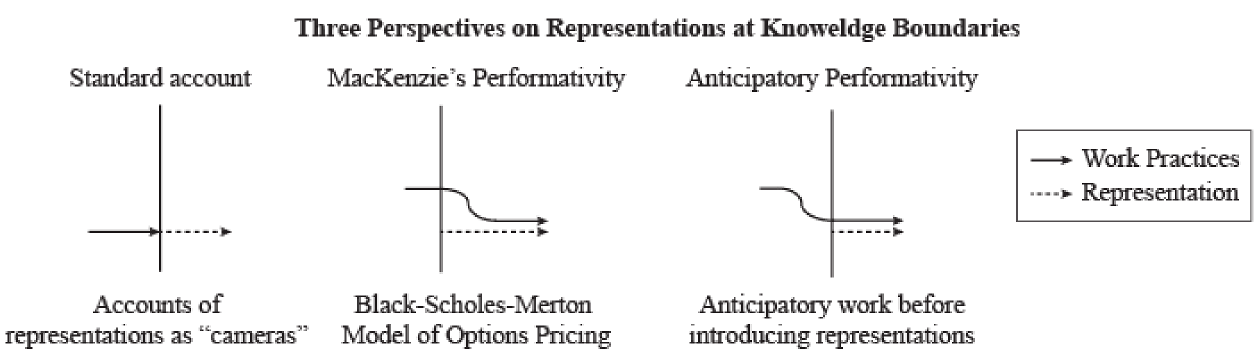

Figure 2. A conceptual illustration of three different types of performativity. In each example, the horizontal axis connotes the passing of time and the vertical line marks the moment when a representation is introduced into interaction at a knowledge boundary. Dotted lines connote the characterization of the world the representation portrays. Solid lines represent the nature of work practices surrounding that representation.

Table 2
Examples of how anticipatory work influenced modeling practices

		Performative Influence on Modeling Practices	
		Influenced Questions Asked *(What?)*	Shaped Modeling Process *(How?)*
Representational Requirement	Appropriate Timeliness	*Energy:* Put off research about how wind shear effects on energy turbines because it would slow down the modeling process *Antarctic:* Put off opportunities to explore improvements in simulated physics because it would slow model run-time	*Energy:* Used a non-standard analysis algorithm (SOM) because its outputs adapted easily to shifting collaborator time constraints *Range:* Refrained from using satellite data in model because it was not available fast enough for "nowcasting" *Dispersion:* Used lower fidelity simulated physics to provide outputs in time for decisions in emergency contexts *Antarctic:* Refrained from speeding up model run-time to manage collaborator expectations
	Perceived Accuracy	*Energy:* Focused research activities on understanding atmospheric phenomena occurring at turbine hub heights *Dispersion:* Focused research on understanding how specific sensors interacted with atmospheric phenomena	*Energy:* Tuned their NWP model to perform to error metrics used by EnergyCo managers *Range:* Modified model physics to accurately predict high altitude winds at a range that tested missiles *Dispersion:* Developed and used a custom NWP model to accurately simulate particle dispersion *Antarctic:* Used model physics known to mimic qualities of the weather radar that forecasters used for observational data
	Perceived Usefulness	*Energy:* Constrained from exploring seasonal weather prediction because researchers could not guarantee partners their efforts would produce useful representations *Range:* Refrained from building UAV scale weather models because ranges perceived them un-useful for current activity	*Energy:* Used SOM's because their outputs were easier for non-scientists to interpret *Range:* Modified an existing NWP model to predict sound travel instead of wind speed and direction *Dispersion:* Developed performance metrics to definitively identify the "best" simulated sensors *Antarctic:* Developed physical simulations to predict blowing snow