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SPECIAL ISSUE: SOCIOMATERIALITY OF IS & ORGANIZING

A TRICHORDAL TEMPORAL APPROACH TO DIGITAL COORDINATION: THE SOCIOMATERIAL MANGLING OF THE CERN GRID[1]

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This paper develops a sociomaterial perspective on digital coordination. It extends Pickering's mangle of practice by using a trichordal approach to temporal emergence. We provide new understanding as to how the nonhuman and human agencies involved in coordination are embedded in the past, present, and future. We draw on an in-depth field study conducted between 2006 and 2010 of the development, introduction, and use of a computing grid infrastructure by the CERN particle physics community. Three coordination tensions are identified at different temporal dimensions, namelyobtaining adequate transparency in the present, modeling a future infrastructure, and the historical disciplining of social and material inertias. We propose and develop the concept of digital coordination, and contribute a trichordal temporal approach to understanding the development and use of digital infrastructure as being orientated to the past and future while emerging in the present.

Keywords: Grid computing, coordination, development, case study, mangle of practice, temporality, digital infrastructure, transparency, sustainable change, performativity, sociomaterial

Introduction

Computing grids have been the harbinger of a wide range of large-scale, geographically dispersed digital infrastructures designed to support communities of scientists (Stewart et al. 2010), and reflect earlier science-based infrastructure such as the Worm Community system that supports geneticists (Star and Ruhleder 1996). Grids continue to be of critical importance not just in supporting the work of natural scientists in areas such as global climate change, the Human Genome Project, or particle physicists' Large Hadron Collider (Ribes et al. 2013), but are also transforming scientific practice in the burgeoning field of cyberinfrastructures (Atkins 2003; Ribes and Lee 2010). More recently, they have been forecasted to become the standard provision of everyday computing services in the future (Gray 2013).

From a technical perspective, a grid is conceived as "a system that coordinates distributed resources using standard, open,

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The appendices for this paper are located in the "Online Supplements" section of the *MIS Quarterly*'s website (http://www.misq.org).

general-purpose protocols and interfaces to deliver non-trivial qualities of service" (Foster and Kesselman 2004a, p. 46). Here, coordination is a wholly technical concern, regarding the provision and distribution of technical resources (hardware and services) by software. A computing grid can be characterized as a globally distributed digital infrastructure, which is decentered, with no single authority being in charge (Buyya and Murshed 2003; Cafaro and Aloisio 2011). At its heart is middleware, which seeks to provide such coordinated resource sharing (Foster et al. 2001), creating a virtual computing center linking and exploiting globally distributed computer centers, and into which is delegated organizational issues such as trust and accountability (Ribes et al. 2013). As such, resource coordination has been extended beyond the single computer or cluster of computers to digital infrastructures on a global scale (Yoo et al. 2010). Grids have become increasingly complex as they span beyond the boundaries of a single organization or institution, and become embedded within diverse sociotechnical domains (Plaszczak and Wellner 2007). The coordination of these digital infrastructures is, therefore, extended to include the global provisioning of resources and services to ensure they are "more than a plethora of balkanized, incompatible, non-interoperable distributed systems" (Foster and Kesselman 2004a, p. 46). As such, a challenge for computer grid infrastructure is achieving sustainable change across multiple installed bases, contexts of use, and evolving organizational goals (Henfridsson and Bygstad 2013).

Thus, not only is coordination central to the technical operation of a grid but it is also a key dimension of supporting geographically dispersed, large-scale collaborative practices (Bietz et al. 2010; Edwards et al. 2007; Gerson 2008), becoming learned as a part of membership and linked with conventions of practice (Star and Ruhleder 1996). Despite these important developments there has been little focus on understanding digital coordination in the infrastructure literature (Grisot 2008), although the literature has recognized a number of other dimensions including being shared, open, sociotechnical, heterogeneous, and having an installed base (Hanseth and Monteiro 1998).

In examining digital coordination, we bring together scholarship on ICT and coordination with recent developments on digital infrastructure to account for how work activities as well as technologies are coordinated and performed. For this study then, coordination of digital infrastructure is both a temporally enacted technical concern (the coordination of distributed computing resources), *and* a concern for the ongoing becoming of coordinated work practices through the performances of using or developing the digital infrastructure. In so doing, we address recent calls by Tilson et al. (2010) to develop novel insight into coordination within digital infrastructure by adopting a sociomaterial perspective to understand how multiple agencies are involved in grid coordination. Specifically, our sociomaterial perspective adopts a trichordal temporal approach to provide a dynamic understanding of the tensions of digital coordination which are embedded in the past, present, and future. We draw on an in-depth longitudinal study of how a computing grid was developed and used among experimental particle physicists at the Large Hadron Collider (LHC) at CERN. The key research question we ask is, *how has digital coordination been performed in the development and use of the CERN grid infrastructure*?

In the following section, we briefly review literature on ICT and coordination and discuss relevant perspectives from recent work on digital infrastructure. We note that both of these literatures have recognized but not adequately developed the role of temporality. After outlining key elements of Pickering's mangle of practice, we draw on and integrate a trichordal approach (Emirbayer and Mische 1998) to further develop the temporal dynamics in our sociomaterial perspective. Our study methods are then described before elaborating the case context of the particle physics grid at CERN followed by the case analysis. We develop our contributions of a sociomaterial perspective on digital coordination within the wider literature on ICT and coordination, and discuss how our findings further our understanding of sustainable change in digital infrastructure.

Views on ICT and Coordination

Coordination is centrally concerned with the integration of organizational work under conditions of task interdependence and uncertainty (Faraj and Xiao 2006; Okhuysen and Bechky 2009). Drawing on an information processing paradigm (Galbraith 1977; Thompson 1967), earlier top–down approaches presupposed a predictable environment that allows ICT coordination to be designed in advance through models shared across an organization (Faraj and Xiao 2006). The focus was on the implementation and use of technology in modeling coordination as an organizational process with information technologies having great potential to improve organizational coordination (Malone 1988; Malone and Crowston 1990). A key shortcoming of these earlier formalized and designed solutions is their inability to account for ongoing work activities that emerge as unplanned contingencies in response to coordination challenges (Okhuysen and Bechky 2009).

Another recent approach attempts to account for the emergent dynamics of coordination, highlighting the temporally unfolding and contextually situated nature of work (Faraj and

Xiao 2006; Kling et al. 2001; Monteiro and Hanseth 1995). The coordination of emergent and provisional collaborative work involves activities and interactions among actors and technologies not explicitly prescribed by management in advance. An important emphasis in this approach is the role of temporality in coordination processes which require synchronization and appropriate resource sharing (Bardram 2000; Kellogg et al. 2006; Reddy et al. 2006). ICT artefacts have also been shown to support the temporal coordination of activity (Bardram 2000; Chua and Yeow 2010). These studies have examined the coordination mechanisms such as tools, technologies, and interactions that encapsulate how emergent practices assist in coordination and allow individuals to realize a collective performance (Kellogg et al. 2006; Kling 1991). Further, they have noted the variable time horizons and temporal rhythms that need to be coordinated in complex work (Reddy et al. 2006).

The approach in these studies goes beyond the how (mode) of coordination toward a focus on the "what and when" (temporal practices) of coordination (Constantinides and Barrett 2012; Faraj and Xiao 2006), an increasing imperative in the increasingly nomadic information environment (Lyytinen and Yoo 2001). These perspectives are deemed critical in understanding coordination of knowledge work in high velocity environments such as trauma centers (Faraj and Xiao 2006), which use a range of technologies in their coordination process (Grisot 2008; Kellogg et al. 2006). These studies suggest useful insights on how actors use technologies that facilitate cross-boundary coordination in time sensitive and volatile conditions. Yet this literature leaves relatively unexamined the temporal embeddedness of coordination processes, and how agents' orientations to the future and past influence how ICT become entangled in emerging coordination practices.

Further, we suggest that in taking ICT seriously (Orlikowski and Iacono 2001), there is a need to extend our understanding of what we term the trichordal temporal approach to coordination to incorporate how ICT materiality is also enacted across time, as nonhuman entities have a past, present, and future distinct from human agencies (Ribes and Finholt 2009). As highlighted by Latour (1992), a concrete "sleeping policeman" coordinates traffic quite differently than a human policeman might, with temporality playing an important role; the former treats every vehicle the same and will do so for many years, whereas the human policeman can let ambulances speed by and will go home at night. In the context of digital infrastructures where generative features lead to their evolution (Henfridsson and Bygstad 2013) while challenging the principles of planned sustainable change (Ribes and Finholt 2009; Yoo et al. 2010), we suggest the anticipated future of the infrastructure influences how coordination is enacted in the present and how past installed bases are conditioned (Star and Ruhleder 1996).

In a recent review of the management literature on coordination, Okhuysen and Bechky (2009) delineate accountability and predictability as integrative conditions for coordinating activity. Integrative conditions provide the collective means for accomplishing interdependent tasks and resolve some of the uncertainties created by interdependence. In our analysis, we draw on these integrative conditions in contributing a trichordal temporal approach to digital coordination.

Digital infrastructures and their different services are used in multiple situated practices across geographically dispersed communities (Hanseth and Lundberg 2001). We recognize that different practices within a collective performance of digital infrastructure development are interdependently enacted by different individuals with various technologies (Constantinides and Barrett 2012). Our approach examines the temporal embeddedness of the multiple agencies involved in coordinating digital infrastructures, agencies that are influenced by the social and material inertias such as the installed bases and conventions of practice (Star and Ruhleder 1996). Our approach explicitly recognizes the relational nature of the infrastructure (Star and Ruhleder 1996), becoming real only in relation to organized practices, thus reflective of the emergent tensions that ensue over time. We also heed the recent critique of digital infrastructure literature as being overly focused on short-term temporal aspects (Karasti et al. 2010; Monteiro et al. 2012; Williams and Pollock 2012), which can limit our understanding of how emerging use and development practices shape the ongoing coordinating of digital infrastructure in the longer term.

We also incorporate what Thrift (2005) and Grisot (2008) refer to as performative infrastructures. Taking seriously the generative materiality of digital infrastructure (Henfridsson and Bygstad 2013), we emphasize the role of technology in integrating and coordinating infrastructure at a global scale, including, for example, the distribution of resources (Foster and Kesselman 2004a; Schwiegelshohn et al. 2010). Algorithms form an increasingly important part of the materiality of large-scale digital infrastructures, such as Trip Advisor (Scott and Orlikowski 2012), reflecting what some have termed the rise of algorithmic culture (Galloway 2006) and algorithmic power (Lash 2007). The material agency of algorithms is an important part of the performativity of these digital infrastructures (Orlikowski and Scott 2008) and provides coordination of work, often without those upon whom they are taking effect being knowledgeable (Beer 2009). A performative perspective challenges "the existence of independent objects with fixed or given properties and boundaries, and focuses instead on situated and relational practices that enact…contingent entities and effects" (Schultze and Orlikowski 2010, p. 9). Such a perspective understands coordination not as fixed, determining, or a mediating platform through which people interact and complete job tasks, but as dynamic and entangled assemblages of the social and the technical, continually produced in practice (Orlikowski 2005) and occurring within "a field of performative material devices" (Pickering 1993, p. 563). Such a performative perspective recognizes that "the world is continually doing things and that so are we" (Pickering 2006, p. 277). This lens offers analytical traction in viewing digital coordination with less focus on whether or how humans use technologies to produce certain outcomes, and more on how humans and technologies are interrelated in practice to produce (more or less) stable outcomes with certain effects in the world (Pickering 1995). In analyzing such coordination, therefore, we adopt what has been termed a *sociomaterial perspective* (Orlikowski 2007, 2010; Orlikowski and Scott 2008), which "posits the constitutive entanglement of the social and the material in everyday life" (Orlikowski 2007, p. 1435).

In sum, our sociomaterial perspective on coordinating the large-scale distributed computing grid promises to contribute to and extend the ICT and coordination literature in two ways. First, it highlights the need to recognize the human agencies and technical performances entangled in digital coordination. Second, temporal embeddedness is an important part of such coordination with multiple agencies involved in coordination across the past, present, and future. In attending to these dynamics of digital coordination, our theoretical contributions draw on Pickering's mangle of practice and extend it by incorporating theoretical developments from Emirbayer and Mische's (1998) trichordal view of temporality—focusing on the interplay of past, present, and future.

Theoretical Perspective

Pickering (1993, 1995, 2002, 2006) describes his mangle of practice theory as ontologically within the "performative idiom." Building upon this theory, our theoretical developments center on the temporality of grid coordination as constituted in a mangling of human and material agency. Pickering's perspective focuses upon achieving a "real-time understanding of practice" (1995, p. 2) by exploring how "human and nonhuman agency…temporally intertwine" (1995, p. xii). Grids are deeply entwined interrelationships between material components (e.g., networks, computers, and software), use (e.g., the analysis of data) and human agents including various computing specialists and science analytics users. In the following subsection, we develop our sociomaterial perspective by first discussing Pickering's (2008) mangle of practice and its view on temporal emergence. We subsequently build our trichordal temporal approach to digital coordination by focusing on how the social and material temporal agencies in the past, present, and future are enacted in the ongoing development and use of the grid infrastructure.

Mangle of Practice and Temporal Emergence

Pickering's central analytical focus is on **agency**: the capacity for action that makes a difference (Giddens 1984; Rose and Jones 2004). The main premise of Pickering's theory is that the human is not central to agency. Aligning with ANT (Callon 1986; Latour 1987), he acknowledges the agency of material artefacts—things can act within a material world on their own. However, in contrast to the symmetry of post-humanist theories such as ANT, Pickering ascribes an imagined future as influencing human agency through his acknowledgment of intentionality. Pickering's notion is of intentions as goals held by humans "that refer to presently non-existent futures states [that humans] then seek to bring…about" (1995, p. 18). Intentionality provides a human purpose while retaining a sociomaterial present. **Modeling** is a process in which futures are imagined based on presently available resources and on how agency might be harnessed to achieve intention (Pickering 1990). It is a future projection translated into present action. Modeling is open-ended with "no determinate destination as…[for] a given model…an indefinite number of future variants can be constructed" (Pickering 1995, p. 19). In this way intentionality can be altered, and is thus itself temporally emergent.

Pickering acknowledges the past as influencing human agency through **disciplinary agency.** This is the pattern of human agency influenced by culture and conceptual knowledge (e.g., the rule following of elementary algebra), which create routinized ways of working (Pickering 1995). Such disciplinary agency creates inertia in action. However in Pickering's analysis, disciplinary agency is rigid as it is not a mere "influence" on discretionary human agency. Rather it is an agency itself since, for example, to practice algebra is to apply the disciplinary agency of algebra without discretion. This disciplinary agency is thus separate from human agency (with its intentionality) as little discretion is available. In the practice of algebra, the rules are as rigid as the material agency of wind is to the practice of sailing.

In the present, material artefacts, such as machines and technologies, can offer **resistance** to human intention in the form of material agency, defined as "the failure to achieve an intended capture of agency in practice" (Pickering 1995, p. 22). Humans may respond with **accommodations** involving the further harnessing of technology and objects in the aim of achieving their intentions (although further material resistance might follow) or with revisions to their goals and intentions (Pickering 1995, p. 22). Pickering uses the metaphor of a **mangle of practice** by which human agency is intertwined with material agency in an ongoing dance of agency: an emerging dialectic in which, through the unfolding of resistance and accommodation (as intentions are sought), human and material agency are constitutively enmeshed (Pickering 1993).

Pickering defines **tuning** as a process by which the mangling of practice is altered as material agency is harnessed and directed through humans creating and altering machines, devices, and software within a flow of material agency (2005, p. 278). Tuning only ceases when it leads to outcomes that make sense to humans and aligns with their intentions, thus stabilizing both material and human agencies. Until this occurs, humans' interpretive accounts, material agencies, and practice continue to evolve (Pickering 1995, p. 81). We, however, argue that tuning involves multiple temporal dimensions; both social and material entities are embedded within multiple temporal dimensions at once. Thus multiple sociomaterial agencies can be said to be oriented toward the past, the future, and the present at any given moment.

Within any given situation there exists a negotiation—a tension and interplay that produces constantly new and emergent forms of sociomaterial existence in which human and material are inseparable. The focus of the analysis is thus decentered from the human and the material, instead focusing on the human–material "mangle"—an unstable and evolving sociomaterial configuration. In summary, work involves maneuvering "in a field of material agency, constructing machines that…variously capture, seduce, download, recruit, enrol or materialize that agency, taming and domesticating it, putting it at our service" (Pickering 1995, p. 7).

A Trichordal Temporal Approach to Digital Coordination

Our analysis examines digital coordination as a temporally enacted dynamic and is attentive to the ongoing becoming of a grid's development and ongoing use. Building on the mangle of practice, we draw upon Emirbayer and Mische's (1998, p. 964) argument that agency is always "oriented toward the past, the future and the present at any given moment [in a] chordal triad of agency" to extend Pickering's temporal dynamic. Only emergence in the present has a reality status, the past and the future being real only with respect to their relation with the present. Within this chordal triad of agency all three dimensions resonate as separate, although not always harmonious, tones. For Pickering, this orientation is only weakly theorized in his definition of modeling and disciplinary agency, and the link or interplay between these concepts has not been developed. Furthermore, the temporal dynamics in his analysis have been largely left to human agency.

Building on Emirbayer and Mische, we suggest that digital coordination can be understood as a temporally enacted process of sociomaterial entanglement. It is configured by the past (arising from social and material inertias including, for example, disciplinary agency and installed software bases) but also oriented toward the future (as emerging plans, modeled performances and anticipated evolution of knowledge) and emerging in the present. Emirbayer and Mische also argue that social agency can only be captured in its full complexity if it is analytically situated within the flow of time. In our context of digital infrastructure, we suggest that the examination of material agency, such as in software, is also strengthened when situated within the flow of time. The installed base, history of tools and equipment use, as well as the anticipated future sciences and evolving capabilities of devices and generativity of software as projected into the future also influence action in the present and thus the sociomaterial mangle. While Pickering recognizes the role of disciplinary agency as constituting what Emirbayer and Mische call "iterational agency," we further develop emergence to emphasize that the connections and relations between the past/present/future are dynamically constituted and potentially altered (Adam 1990; Barrett and Scott 2004). Each emergence irreversibly affects everything else, not just the meaning of all past and future, but all of present reality and its possible futures (Adam 1990). Therefore, in our perspective, emergence refutes linear causality of change processes as being means-end driven and goes beyond classical theories on the separation of past, present, and future.

We follow Emirbayer and Mische's assertion that "for each analytical aspect of agency one temporal orientation is the dominant tone, shaping the way in which actors relate to the other two dimensions of time" (p. 972). Disaggregating the temporal dimensions of sociomaterial agency and exploring which orientations are dominant within a given situation allows us to suggest that each primary orientation in the chordal triad encompasses, as subtones, the other two as well, although this "chordal composition" can change as actors respond to the diverse and shifting environments around them during the ongoing tensions of resistance and accommodation. We summarize our trichordal perspective on temporal dynamics in Figure 1, showing how the present emerges through mangling influenced by the dynamic harnessing of past and future. The recursive arrows linking the past, present, and future show how emerging agencies can be influenced by each. Finally, these arrows also highlight that the cycle of resistance and accommodation occurs in the performativity of the mangle. Together all of these elements form the chordal triad of agency within our analysis.

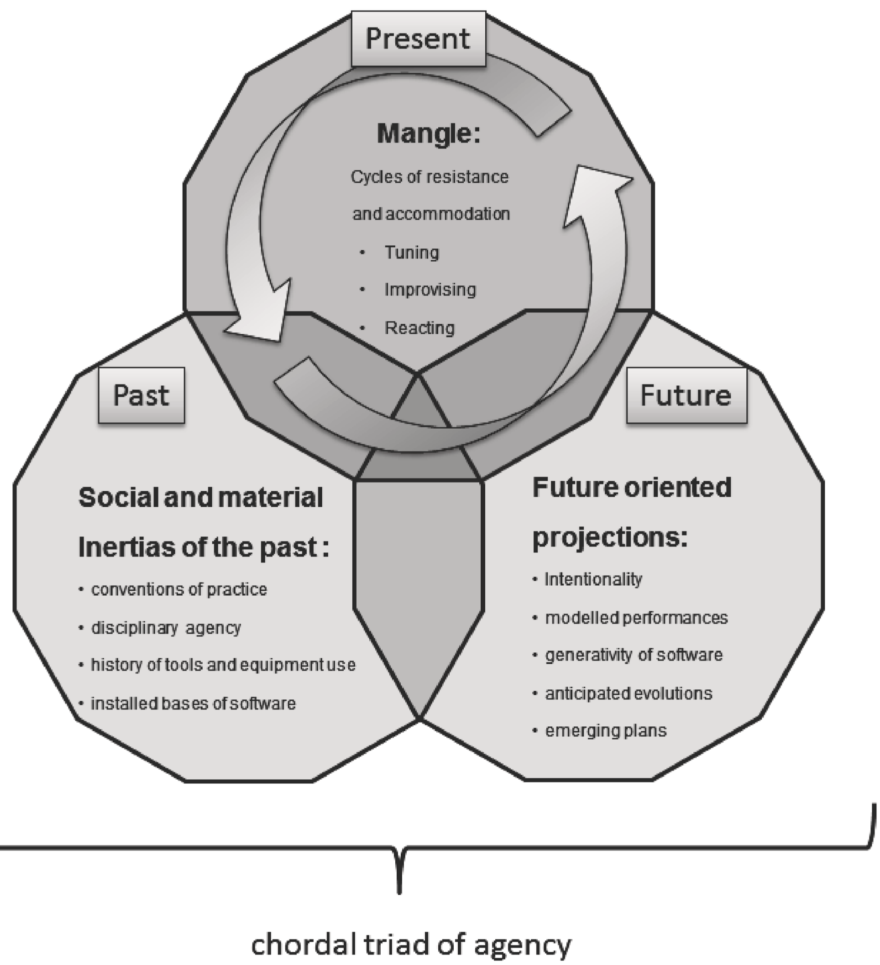

Figure 1. Digital Infrastructure Coordination as a Temporally Enacted Dynamic

As developed in our case analysis, the present tension of maintaining (or obscuring) transparency of the digital infrastructure emerges through harnessing software capabilities to control the flow of computational analyses of particle physics job tasks by adding layers of middleware to the grid. Where multiple communities participate in the tuning process across globally distributed locations—each with the inertia of installed bases and conventions of practice—the integration of these diverse histories will influence the grid coordination. "The past, through habit and repetition, becomes a stabilizing influence that shapes the flow of effort and allows us to sustain identities, meanings, and interactions over time" (Emirbayer and Mische 1998, p. 975). Within the contingencies of the moment, future software engineering capabilities—such as those prescribed in Moore's law—and the generativity inherent in digital infrastructure (Henfridsson and Bygstad 2013) shape emergent action. These, along with shifting plans and goals, work to configure a bespoke rather than heterogeneous grid.

Methodology

A systematic field study was conducted between 2006 and 2010 of the development, introduction, and use of a computing grid by the CERN particle physics community in preparation for, and upon the launch of, the Large Hadron Collider (LHC). This included interviews, observations, and reviews of documents. Seventy interviews were recorded and transcribed (see Appendices A and B). Ethnographic observations were undertaken including at five 2-day WLCG (Worldwide LHC Computing Grid) meetings in the UK, two conferences, four visits to data-centers (London, Edinburgh, Glasgow, and Oxford), ten social events, and two week-long visits to CERN. Two half-day, one-to-one training sessions were attended on particle physics and LHC analysis, and on running physics analysis jobs and developing the WLCG. Documentary sources were reviewed including wiki pages, journal articles, websites, software code, configuration files, and a 409 page workbook that provides a manual for undertaking physics analysis using the WLCG. Key sources are listed in Appendix C.

A four-stage analysis process was used (Appendix D, Table D1). The first stage involved reading the empirical material and producing basic summaries of what was happening (using terms derived from the empirical material) when the grid was developed and used. These summaries provided contextualization (Klein and Myers 1999) aiding understanding, at its broadest level, of what was going on. In keeping with empirical studies using the mangle of practice, such summaries focused on the temporal unfolding of the case, moving from the abstract level of the LHC to the specific details of doing particle physics data analysis. In addition, a sparse form of open-coding was undertaken of interviews to provide anchor points to make the data more manageable (Appendix D, Table D2).

For the second stage of analysis, the mangle of practice formed a repertoire of lenses (Deetz 1996) against which empirical material was compared. Each element (or lens) of the theory was considered in providing an understanding. Pickering (2001) argues that the units of analysis have to be found in empirical research. In this analysis the temporal aspects of the case were especially evident, in particular the looming LHC start-date, and the inertia of previous grid developments.

The third stage of analysis involved a more systematic analysis of groups' interactions with the WLCG as it came into being, seeking that which proved interesting while remaining aware of potential bias (Alvesson and Kärreman 2007). Here temporality was revealed within the mangling of the grid through the harnessing of software agency by physicists. Ten further interviews were then undertaken to elaborate on the software development practices and to critically assess the emerging analysis. This analysis was presented at a WLCG conference to help validate its description. We subsequently revised our theoretical perspective, weaving temporality in a more explicit manner to further our analysis of the emergence of the grid infrastructure—and through this process extending the mangle of practice with our trichordal temporal approach.

The fourth stage of analysis drew upon the theoretical framework defined above to guide analysis of the data in terms of the agency within coordination practices. We compared and contrasted the data, refining our analysis and so detailing the significance of future and past within human and material agency as the grid was mangled. Appendix E provides evidence of the analysis of the temporality of the case, as detailed in Table 1. Appendix F provides evidence samples from the documentary evidence referred to in the case. Appendix G provides a glossary of key technical terms.

The approach adopted aligns with Sandburg and Tsoukas's (2011) suggestions for developing sociomaterial theories by focusing on what "practitioners routinely did, with others and tools, for what purposes" and what mattered to practitioners, and "how practitioners competently perform doings and sayings with what results" (p. 351).

Case Context

The Large Hadron Collider (http://lhc.web.cern.ch/lhc) is the largest and most powerful particle accelerator in existence. Its 27 km ring, hidden 100m below Geneva, Switzerland, accelerates subatomic particles called hadrons to close to the speed of light, then collides them. CMS (Compact Muon Solenoid; http://cms.web.cern.ch), the focus of this paper, is one of four experiments measuring and recording vast numbers of these collisions, producing vast quantities of data, equivalent to 15 million gigabytes of data per year or a DVD every 5 seconds. Experiments last for over a decade and go through several phases of activity from design through to decommissioning, the pivotal moment being the actual launch of the collider and the start of data-taking. Associated with each experiment are Virtual Organizations[2] consisting of thousands of particle physicists at numerous universities and labs seeking to analyze this data and discover new forms of physics (including searching for the famous Higgs boson[3]). The CMS experiment's virtual organization consists of around 3,600 scientists from 183 institutes in 38 countries, requiring

[2]This category is derived from the case study where it is used to denote the collection of human actors with access to the grid within their experiment. Like Ribes et al. (2013), we use the term as shorthand for a geographically distributed organizing activity. It is not aligned with its use in the IS literature.

[3]The standard model of particle physics has been extremely successful in describing particle physics data since its formulation in the 1960s and 1970s. However, the model requires the existence of a particle called the Higgs boson, and hence the desire to discover this is extremely strong. As of July 4, 2012, CMS observed a five-sigma signal of a new particle with mass 125GeV that is consistent with expectations of the Higgs; however, more research was needed for a definitive discovery to be made (CMS 2012). These results were then combined with those from ATLAS to achieve discovery and Peter Higgs (jointly with François Englert) was awarded the Nobel prize physics in October 8, 2013.

Table 1. Description of the Temporal Analysis Tables in Appendix E

Evidence of the present tensions around grid transparency	
E1	Resistance from the grid faced by computer specialists in the present
E2	Tuning the grid through the harnessing of CRAB in the present
Evidence of future orientation for both human and material agency	
E3	Analysis of human intentionality within the case
E4	Analysis of future expectations of material trajectories
Evidence of past inertias evident upon the present practices	
E5	Examples of the installed base of particle physics technologies upon which the WLCG infrastructure is founded
E6	Disciplinary agency and conventions of practice of particle physicists
E7	Disciplinary agency and conventions of practice of computer specialists

vast, unprecedented computing and data storage resources. Due to a range of political, funding, and management issues "*grid technology was a natural choice*" (d30) for providing the computing and storage needs of the LHC experiments.

In 2001, the WLCG was established to build this resource (Pearce and Venters 2012) and gained funding by collaborating closely with other sciences and by integrating with national science grids (Eerola et al. 2003; Pordes et al. 2008).

A large group of people we call computing specialists, many of whom also had training as particle physicists, collaborated to build and maintain the WLCG (Zheng et al. 2011). They broadly shared the desire of building a grid (see Appendix E, Table E3) based on computer science ideas and many had significant experience delivering high-performance computing, building, and running data centers, writing middleware software, producing and monitoring software, and managing security services (d33). In its first two years, the WLCG project built a grid of around 40 sites (i.e., data centers in the grid) that the experiments used for simulation work. By 2004, 78 sites with 6,000 computers were available. By 2011, the WLCG consisted of 600 sites with 150,000 computers across 62 countries.

Coordinating the Organization of the WLCG

All computers within the WLCG run grid middleware to provide the virtualized computing service. The aim of the middleware is to abstract the globally distributed resources within differently administered sites and provide them as a service (Berman et al. 2003). Middleware aims to coordinate the use of resources to ensure they are efficiently managed (Foster et al. 2001) and appear to the user as a single, huge virtual computing system.

Using the WLCG for CMS experiment analysis requires physicists to write analysis software (usually using the C++ language) for their specific analysis task and to submit this to the grid along with the details of the data needed. The WLCG middleware then breaks such analysis "jobs" (a block of computation run on the grid) into potentially millions of parallel jobs, identifying the relevant files from across the grid, submitting the analysis software and the data files to the available grid computers, ensuring jobs run successfully, and recombining the final result.

As particle physicists' analysis jobs increased, and grid complexity increased, many jobs failed. One particularly problematic part of the grid's middleware was the workload management service (WMS), which coordinated the allocation of jobs to the distributed resources of the grid. In addition to the challenge of getting the WMS to work, a range of different problems occurred (see Appendix E, Table E2) as physicists began to use the grid for their analysis and testing in preparation for the LHC launch. Prior to the LHC running as a beam, CMS were analyzing the cosmic rays shooting through its detectors and producing Monte Carlo simulation data.

To support the physicists, the computer specialists devised a global grid user support (GGUS) messaging system with the aim of distributing user support services across the global network of computer specialists who were usually based at tiered grid sites. This service would help scientists respond to problems. In particular, in keeping with the idea of a grid as providing "utility" computing, they believed that physicists did not need to understand why jobs failed or disappeared "*into a black-hole*" (as physicist i13 described it). For this reason the WMS returned a so-called "zero-code" (meaning success) in all cases where the grid had run something, whatever the result of it running.

```
[CMSSW]
total_number_of_events =  -1
number_of_jobs         =  10
pset                   =  reco_RECO_tsw.py
datasetpath            =  /Boosted_Quark_To_ee_2TeV/tsw-my5e32HLT_2-00TeVu_v1-
                          5c8626423b3ca515cf3687fd35dfb13a/USER
dbs_url                =  http://cmsdbsprod.cern.ch/cms_dbs_ph_analysis_01/servlet/
                          DBSServlet
output_file            =  mcFile_GEN-SIM-bothRECO_spec412ReconV2.root

[USER]
ui_working_dir         =  crab_bstd412Recon_2-00TeVu_v2
return_data            =  0
…
```

Figure 2. Example Fragment of a CMS Ph.D. Student's crab.cfg File

> *Job success was always zero…no matter what happened....This is not very useful for physicists. For one thing it is impossible to monitor if something is going wrong* (i4).

Given that jobs could fail for a range of reasons, including due to the physicists making errors in their own analysis code (d22), physicists complained that zero-codes made it extremely hard for *them* to understand and resolve failure.

> *In this grid system, sometimes my job ends up somewhere in Germany…and quite often it doesn't work…I am a step removed from…the jobs that are running* (i6).

Developing CRAB as a Physicist Response to the Problem of WMS

Faced with the problematic WLCG the CMS physicist's group developed CRAB (CMS Remote Analysis Builder) software specifically to help undertake their analysis quickly and easily (d12, d18, d22). CRAB was "*intended to simplify the process of the creation and submission of CMS analysis jobs into a grid environment*" (d18) and provide an "*analysis wrapper*" (i13) around the grid. CRAB was complex software, undertaking sophisticated interaction with the WLCG middleware in order to run analysis jobs on behalf of particle physicists (d22). To use CRAB, the physicist specified in a text file (crab.cfg; see Figure 2) the parameters of the job they were undertaking. The CRAB software then packaged the analysis jobs and instructed the WLCG to run the jobs using CMS data. In this, it interacted directly with the WMS to run the job and return the results. Details of how to install and use CRAB were posted on frequently asked questions websites for the CMS community, enabling its widespread use among the physicists (see Appendix F).

CRAB Coordinates the WLCG

Faced with job failure and zero-codes, physicists experimented with the "`crab-kill`" command to simply remove problematic jobs from the grid, killing jobs that subjectively seemed to take much longer than the rest. The physicists harnessed CRAB to exploit WMS features intended for its maintenance, by including a facility to *white-list* and *blacklist* through crab.cfg commands (see Appendix F, Item F1).

Using these commands it was possible for physicists to force the WMS to exclude particular areas of the grid for jobs, or force jobs to run on particular computers within the grid just as the computer specialists might do in testing, although, as one developer asserted,

> *in principle users should not [use] white-listing or blacklisting since [they] should assume the grid infrastructure is a failure-less infrastructure* (i12).

The GGUS could also be circumvented. If the physicists knew where on the WLCG their jobs had run, they could interrogate job failure, and even telephone the site directly:

> *If there is a site-manager that is helpful/available there and I want to submit directly to this site, I can do it [using CRAB]* (i13).

On the other hand, for computer specialists, and the grid, white-listing and blacklisting through the CRAB created a vicious circle that frustrated their ongoing development of the WMS. It was difficult to test fixes or improvements to the grid, as CRAB blacklisting avoided broken sites, making it difficult to get the volume of jobs needed to monitor usage patterns or monitor failures. Bottlenecks occurred as parts of the grid became heavily used and inefficient, while other parts remained unused. While the location of particular popular data sets contributed to this, it was hard to understand the decisions users had made in blacklisting or white-listing:

> *There are lots of reasons…personal preference, data location…all those reasons, so it is not a simple answer* (i1).

Furthermore, once a site was blacklisted it was difficult to persuade users to remove it from the blacklist:

> *If a site fails it is blacklisted and if the fault is corrected nobody un-blacklists you* (i1).
>
> *Users…started feeling that some sites are better than others* (i12).

The coordination of job flows and computer usage (resource allocation) across the grid shifted from being controlled by WMS, to being jointly negotiated by WMS and CRAB, and computer specialists and particle physicists. In the process, the grid infrastructure became less efficient overall for multi-purpose use, with multiple layers of added software tailored to suit specific and immediate needs of physics yet less able to function as a heterogeneous utility computing service coordinating across multiple scientific groups and specialities.

Case Analysis

In examining digital coordination, we focus on the CERN grid emerging through the ongoing tuning process as CMS physicists sought to exploit WLCG for analysis of their experiments and as the computer specialists sought to expand, develop, and maintain the grid as a heterogeneous infrastructure. We first analyze the tensions that predominate around gaining grid transparency in the present; second, the tension of developing and sustaining heterogeneity of grid infrastructure, which orientates to the future; and third, the inertia of different installed bases, disciplinary agencies, and conventions of practice, which orientate to the past.

Resisting and Accommodating Transparency: Orientating to the Present

The computer specialists faced significant material resistance in their pursuit of a grid for the LHC and science (see Appendix E, Table E1), many of which only became apparent as the grid was used by physicists for analysis jobs. The computer specialists therefore needed the physicists to run their jobs to test and improve the grid, even though it was inevitable some jobs would fail:

> *A lot of the lessons we've learnt over the last three years, about how you set up various services, the configuration, the redundancy, we didn't know then, we didn't know how experiments would use the services* (i27).

In response to the WLCG resistance, computer specialists harnessed WMS middleware, and zero-codes (from the WMS), in an attempt to ***tune*** the grid to help accomplish physicists' computations, and to achieve their own intentions. Job failure was a breakdown in the coordination of the grid by the WMS and thus demanded attention. When jobs failed, the specialists believed that they were responsible for resolving them. They set up GGUS as a user support system to provide a means for reporting problems or broader grid concerns. Furthermore, their work also focused on improving the WMS to extend its efficiency. As one explained,

> *the idea is to try and make it so [grid users] don't need to know any more than that [how to submit jobs to the grid]. In the old days, they used to have to log on to some different computers and manage their own affairs and somehow you want to take that away from them so they can just submit the jobs, get the output and do the physics with them* (i65; see also Appendix E, Table E2).

Computer specialists had ceded coordination of the grid to the WMS with the aim of providing computation in an abstracted, non-transparent manner to physicists. When the grid resisted efficient coordination through failed jobs, physicists saw this as a breakdown in coordination—an exception—and sought to tune the grid. WMS and GGUS mangled the practices of ***using*** the grid to limit transparency and appear utility-like to physicists. When jobs failed, the physicists would continue to receive a utility-like service; they would have to use GGUS (just as when power cuts occur, homeowners can only call the power company and wait). It was, therefore, logical to provide a zero-code since the physicist could not act upon failure (any more than a homeowner could act if told the power cut was caused by specific substation machinery).

For the physicists, grid resistance was only one among many reasons for job failure: their analysis code could be faulty, their own CMS's software problematic, and their experiment itself was unfinished and recalcitrant. However, for them, responding to such material resistance was their usual practice of work, which often involved harnessing software in order to accommodate complex, unexpected resistance (an extreme example was that a previous CERN experiment developed software to correct for the resistance of the material agency of the moon's tidal impact on the land,[4] and for high-speed trains leaving Geneva station[5]). The grid was simply one part of a complex technical apparatus they required to discover new physics:

> *This is just a tool, like a particle accelerator. To understand what happened in the Big Bang* (i4).

The main concern physicists had with using GGUS and accepting the zero-codes was that the opaqueness of the grid (so central to the grid concept and the intentions of the computer specialists) went contrary to their experimental practices of seeking transparency through using software to analyze the computational data from messy LHC particle collisions to gain clarity.

> *[The grid] is mostly annoying because [particle physicists] are used to transparency, and the transparency goes away* (i70).

> *Most particle physicists want to roll their sleeves up and get involved in all the technical detail of how it's done. And it's always been that way. You rarely would get somebody going to do their PhD in a particle physics group who said: oh I don't want to know about computing. I just want to do the analysis. It just doesn't happen.…It's always in the mentality* (i42).

In response, the CMS particle physicists harnessed software (first the CRAB kill command, later white-listing and black-listing) in tuning the recalcitrant grid based on their intention of enabling computational analysis to be undertaken quickly and easily.

While the planned grid infrastructure was to act as a utility, it was built using a layered modular architecture based on internet technology, which made it possible to write software that accessed the application programming interface (API) of the WMS middleware components themselves, which was necessary for CRAB to undertake job submissions. This API also supported the maintenance software of the computer specialists, providing an interface to blacklist and white-list for testing purposes. Exploiting this, particle physicists could circumvent the WMS as job allocator to render the grid transparent by themselves coordinating the allocation of jobs to sites by improvisation.

Harnessing CRAB middleware created significant resistance for the computer specialists (Appendix E, Table E1). The following quote explains their challenge:

> *The idea is that [WMS] takes all your jobs and manages them for you, submits them to the right place, so you send them there and forget about them until you all come back. But on [your experiment's interface such as CRAB] you can implement most of this stuff, if you want to, to your own satisfaction. And we find people have done that* (i40).

At the end of the case study period, the mangling of the grid continued and CMS physicists went further in circumventing the grid's WMS by developing a *"catalogue of its data"* (i13) and a monitoring system "*that reports independently the situation of the infrastructure as they see it, not as the [computer specialists] see it*" (i11), both of which fed into CRAB, and thus reported to users on grid-sites' effectiveness.

Modeling Digital Infrastructure: Orientating to the Future

The tuning of grid job allocation and workload management by the physicists and computer specialists was, to a significant degree, projective, with human and material agencies shaped by future plans and intentions as well as the demands of the soon to be launched LHC and ensuing experimental outputs. Most prominently for the particle physicists, their intentions toward the WLCG lay in the success of the CMS experiment, winning Nobel prizes and discovering new physics (Appendix E, Table E3). They were aware of how difficult the collider launch would be, and were keen to avoid anything inhibiting rapid access to the experimental data and the ability to analyze that data quickly once the LHC launched.

> *We have a problem. We have to solve it….There's no can't. We have a definite goal that we have to provide in eight months!* (i40).

> *A hard deadline is when the LHC is switched on. By that time the computing infrastructure has to be ready, so that is why there was just this big push* (i59).

CMS particle physicists were driven by this intention of exploiting grid infrastructure to deliver "new physics" quickly once the LHC started, particularly as they were in competition with another LHC experiment (ATLAS) for any discovery involving the LHC.

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[4] http://cds.cern.ch/record/250463/files/CM-P00061237.pdf.

[5] http://cds.cern.ch/record/334095/files/sl-97-047.pdf.

The WLCG was essentially a grid *for* the LHC as epitomized in its name—the Worldwide LHC Computing grid—and the modeling of what would happen once the LHC was running was instrumental in modeling the infrastructure for both the physicists and computer specialists. While projected as a global infrastructure, it was no accident that the infrastructure was hierarchically organized fanning out in tiers from CERN's huge data-center close to the physical experiments. The construction of the WLCG was part of the construction of the LHC experiment itself, and the ongoing use of the grid was influenced by the modeling of future requirements from its launch, both in terms of detailed shared goals and objectives for the WLCG development project (d6, d7). The LHC also projected a scale and size for the WLCG, with activity aimed at ramping up its capacity and quality for the LHC launch. Solving coordination challenges in the present were accomplished through maneuvers and selective attention to future goals, and anticipated resistance to meeting those goals.

In particular, they anticipated a future "hump" year when the LHC would be launched. When the LHC was turned on, massive amounts of data would be generated and need to be moved and analyzed as quickly as possible if a discovery, and associated Nobel prize, was to be achieved. The years prior to the hump year were focused on innovation, testing, ramping up, and scaling out the grid; the years after it were known as "production," where things will stabilize and computations become routine, confirming and developing the initial discoveries.

> *[CERN is] where all this clever technology was invented, you know, real sort of original developments in computing to meet the challenges…that's the way it progresses…this is tricky now. By 2014, 2015, this will not be challenging anymore, okay? So the hump year, the year you've got to get right [is the launch year]* (i2).

However, one part of modeling the achievement of this deadline was a sense focusing on speed rather than quality *per se*. An interviewee explained:

> *Particle physicists always get the job done by and large because they are driven by one fundamental thing. They want their experiment to work when the [particle]beam gets into the accelerator, okay? And that transcends everything else they do….And they do…what's necessary according to the time scale. So the closer it gets to switch-on, the more they'll do quicker ad hoc jobs to get it done* (i42).

The digital infrastructure needs to coordinate immense data sets among competing scientists who are seeking to analyze and exploit the most interesting findings first. The coordination needs to cope with anticipated points of peak use, known to revolve around the work cycles of the experiments in the future. Current coordination is thus mangled by the anticipated future analysis activity.

This projective coordination configures a specific grid, one that anticipates the performance required to meet the needs and timing of the beams, large data sets, tiered location of experimental groups, and the discovery of new physics—a bespoke future grid for sustaining CMS. That this included white-listing and blacklisting is "good enough" for the physicists, focused on exploiting the current and future infrastructure and the current and future data for their experiments. But at the same time it was problematic for computer specialists focused on anticipating resource efficiency needs. Although the specialists were acutely aware of the importance of meeting CMS computation needs and for expediency, their future orientation was also to develop a heterogeneous grid that could support all LHC experiments and other e-sciences as well. They were concerned that the focus on a bespoke grid (such as was created by the CRAB white-listing) was detracting from their ultimate goal:

> *Any functioning grid in the future will have to be heterogeneous, okay, and that's what we don't have in particle physics…the [WLCG infrastructure] takes a cross section through and…it's actually doing a very specific solution now, okay?…. bespoke really….If you never [focus on the heterogeneous grid] and you only do [a physics grid], you run the risk of never ever building a useful system that will ever work* (i42).

To work toward developing a more efficient grid infrastructure, diverse monitoring systems were developed to identify lagging sites. A professor (Steve) produced an influential dashboard called "Steve's Jobs" (d26) which ran nightly, producing a picture of job success on the UK grid sites mapped in colors (red, orange, green) and served not only to compare the current performance but also to predict which sites would be more efficient than others in the future (for example, a red color highlighting low future efficiency). These predictions shaped the practices of the computer specialists (e.g., d33) by identifying where efficiency gains were needed and which sites would need extra support. To meet the goals of building a heterogeneous and general purpose coordinated grid, computer usage and data analysis needed to be adequately distributed across the grid's network, rather than concentrated on select sites with a history of successful computation as selected by CRAB white-listing. Technical specialists were also keen that GGUS be used to support failed jobs and red dashboard sites now and in the future, allowing the globally distributed specialists to learn to improve future grid coordination, and allowing them to manage the anticipated future demands on their time.

The materiality of future technology around the CPU, servers, networking, and programming influenced computing specialists' practices in influencing grid coordination. For example, when the researchers visited the CERN data-center they were shown a number of future-oriented prototype devices, delivered by IT manufacturers for evaluation (with some manufacturers maintaining research and development facilities on the CERN site to aid this relationship). This relationship is detailed in CERN's official history:

> *Researchers at CERN work closely with industry to test and guide the development of cutting-edge technology, and to establish open standards to make the grid as widespread and easy-to-use as the Internet* (d32, p. 179).

In this way, and through modeling costs based on theories such as Moore's law (Moore 1965), the anticipated future of computing influenced the immediate practices of the computer specialists, and their harnessing of technical devices within the present grid. In particular they imagined the future cost of computation falling, and the purchase of new hardware was left as late as possible to maximize value.

The grid trajectory and its middleware were materially oriented toward a future in which it would evolve and innovate further. Architected as an open, service-oriented architecture with large numbers of APIs, the WLCG of today was incomplete and its generative features projected a different material future. APIs proliferated, pointing to an anticipated future grid with currently unknown capacity and capabilities for directing computation resources to new science experiments. Standardization activity, which sought to restrict and close down the generative potential embedded within these APIs (closing down some of these imagined futures) lagged.

> *We called this the hourglass model…you have a lot of Middleware at the bottom, you have a lot of experiment software at the top but in between there should be a very well defined thin API which is understood by both sides and agreed. And essentially that just never happened. So at the bottom there was a proliferation of middleware with a variety of different interfaces* (i2).

The present grid was focused on scaling outward both in its software (through APIs) and in its hardware, in readiness for the future LHC launch and possible new physics, and new computing requirements. Designing for such scaling was not trivial, as the expected data center sizes (i.e., power and cooling demands), network demands, and software needs to support the CPUs needed at the day of the LHC launch were not based on current material capabilities. Similarly, GGUS was architected for this future imagined need for scalability of user support, in which the management and organization of a grid was itself distributed and automated, and thus made it a self-organizing support system.

The future coordination of the grid was mangled with the anticipated future of technology including positive and negative changes in hardware and software, to act as a yardstick to compare the grid present performance:

> *[Computing elements (CEs) of the grid becoming] overloaded is an issue. So we could have more than one CE to a site. The next generation of CEs need to be lighter, so they can handle more jobs. I don't see this as being a problem in the future, but it is certainly a problem at the moment* (i1).

Thus, the next generation of computing and physics were shaping how computer specialists were accommodating grid coordination in the present as they sought to achieve a grid that would provide computation services to a wider heterogeneous community, while the physicists were tuning grid coordination to deliver the sustainable coordination they needed to ultimately reach the prize of discovering new physics.

Historical Disciplining Through Competing Social and Material Inertias of the Past

Grid coordination in the present was also orientated to the past, influenced by the historical flow and inertias of experimental particle physics. Physicists have been temporally disciplined into a rhythm of experiments and sporadic races: physicists go through periods of pushing their science forward through new experiments and being limited by contemporary engineering, and thus pushing demand for innovation—be it superconducting magnets, electronics, or computing (see Galison 1997). However, past innovations form part of the mutual understanding of what CERN is: a place where initiative is taken and problems are solved.

Furthermore, physicists have a long and successful history of working in large-scale collaborations and using advanced computing skills to track and define elusive particles in cooperation with others. The field evolved through maintaining set roles and harnessing various tools, such as accelerators, mathematics, and computers, which were incorporated into experiments and ingrained within their work responsibilities—for example, as Monte Carlo simulations to facilitate experiment predictions. As Galison (1996) recounts of early nuclear-weapons and particle physics research in the 1940s and 1950s.

> The computer began as a tool—an object for the manipulation of machines, objects, and equations. But bit by bit (byte by byte), computer designers deconstructed the notion of a tool itself as the computer came to stand not for a tool, but for nature itself (p. 156).

The CRAB analysis code was their model of nature (employing the same techniques of Monte Carlo), and manipulating this model became the essence of doing particle physics.

> *I think what I am doing [when coding] is still physics, because I am trying to get to physics analysis. It is a very fuzzy line….We need computing like we need accelerators, and like we need mathematics* (i4).

Physicists style of computing is not, however, always elegant:

> *[We] are…very dirty programmers…and will use the fastest way to get at something…do not use structured program design unless forced to… usually want the fast hack* (i4).

Physicists' disciplinary agency learned in the past directs the high levels of improvisation in coding and relatively low levels of formal structure. The role of software coding in physics has developed into a form of experimentation similar to their physics experimentation: never to reach the status of a "finished" product.

> *Since [they've all] been Ph.D. students, they've been trained in the way experiments work. They've seen how it's happened in experiments and then they go on as a postdoc into an expert and they take some of that with them. So I think somewhere out [of] this there's a legacy of this through their working lives* (i58).

These conventions of practice discipline physicists toward particular knowledge bases and ways of working, which shape how computer coding is accomplished and how software is harnessed in mangling the grid infrastructure.

The physicists saw programming as their response to poorly understood resistance. When faced with unexplained zero-codes and failed jobs, their responsibility was to trace the source of error using software. As this proved difficult, they then sought to coordinate job allocation on the grid infrastructure through killing jobs or exploiting CRAB to make it easier—harnessing software in response to resistance. Resolving their computer problems was thus influenced by a disciplinary agency of "fixing problems", not caring how such a fix was made.

Physicists' desire for white-listing was also influenced by past experience with the infrastructure of cluster computers (server farms), laptops, and supercomputing; white-listing aligned with their knowledge of their installed bases. When discussing the grid, physicists used terms from these earlier architectures such as "*my site*" (i13), machines, and described the grid as a big cluster computer, thereby challenging the virtual single utility model of grids. Indeed, many modeled the grid in terms of these older technologies:

> *We just see the grid as an extension of our local PC farm* (i66).

> *A lot of people believe that the parallel computing cluster is the same thing as the grid* (i8).

> *The principle difference between local clusters and global clusters is fairly small…[it's] the next logical step in computing after [cluster-computing]* (d32).

In contrast, the disciplinary agency of computing specialists (Appendix E, Table E7) shaped their programming style to be less orientated to quick fixes and instead trying to build and design a coherent, scalable grid infrastructure with elegance and sophistication that would require less maintenance and run effectively for all LHC experiments as well as for the broader science community. The contrast between the two conventions of practice is stark:

> *I suspect if a computer scientist did this, they'd take a much more theoretical approach. It might be rigorously more defensible, it might even be the better way of doing it in the long-term but in the short-term you probably wouldn't get the results so quickly* (i58).

The discipline of computer science, and the long experience of those involved in developing high-performance computing for particle physics foregrounds the importance of optimal coding techniques and scalability. The computer specialists consider themselves pioneers of computing and have historically wrestled with new computers. They often push the limits of the possible, and see themselves as responsible for extending the boundaries of computing. For example, their history included the use of prototype-recalcitrant computers such as the third ever CDC-6600 supercomputer designed by Seymour Cray, an early installed base that reinforced the importance of efficiency in computing and the specialists' role in obtaining reliable coordination. As the computing division leader recounted,

> *The introduction of such a complex system was by no means trivial and CERN experienced one of the most painful periods in its computing history. The coupling of unstable hardware to shaky software resulted in a long, traumatic effort to offer a reliable service* (d31).

These pioneering experiences with cutting edge technology are often invoked in descriptions of the grid. Such systems form a benchmark against which the current systems are compared and orientated. Furthermore, this history encapsulates the current form of the grid, as the huge CERN data center (built for these older systems) is used to host the largest site on the grid (and the center of its hierarchy). Similarly, existing national science centers (such as Rutherford Appleton in the UK) were preferred for housing the next largest "tier 1" sites, in part due to previous success supporting particle physics. These sites had greater resources and, it was believed, were more reliable than most other sites in receiving large data files and maintaining file access for ongoing analysis; it was trusted that staff would run them well.

> *I'm far more worried about the Tier 1's, some of which are at places where there is not a tradition of very large computing for particle physics. Now at Rutherford there is, right? And so we have some confidence. But other places are brand new centers and, you know, it's a tough business* (i2).

These earlier software systems provide inertia in shaping grid coordination. Like other information infrastructures, grids rely on an installed base of standards and software implementing the standards (including TCP/IP, Linux, x86 architectures, and storage standards). The WLCG also incorporated existing software and standards developed within particle physics on earlier systems and experiments, in part due to their expertise with these standards, the sunk-cost of their development, and the installed base of users.

> *People have put so much effort into developing these systems in the past, they think we can continue using it and adapt it and develop it and modify it so that it fits into the grid world. The same goes for CASTOR—that was a CERN storage manager, that's what it stands for CERN Advanced STORage manager. So [CASTOR] has had bits kind of added on to them so that they can talk to [the grid]* (i26).

Finally, the computer specialists' practice was influenced by the invention of the World Wide Web by Tim Berners-Lee working at CERN, and this technology's proliferation around the globe. The Web formed a historical model against which the grid, as a potentially radical new system, was understood.

> *CERN invented the web, so CERN is going to bring you something good* (i8).

> *Around the time the web was developed, no one, not even Tim himself was predicting what happened later. Could that happen with the grid? Maybe* (i27).

The Web, however, also acted as a future model against which practices of innovation by both computer specialists and particle physicists were justified.

Discussion

Our sociomaterial analysis of the LHC grid demonstrates how a trichordal temporal approach to digital coordination can show how the emergence of infrastructure is more than a technical concern of providing and distributing resources (Chua and Yeow 2010; Crowston 1997). While in accord with earlier practice-based studies (Faraj and Xiao 2006; Kellogg et al. 2006) that account for the emergent nature of coordination, we additionally account for both social and material agencies as a temporally enacted tuning process. Furthermore, the finding of our study on coordinating the grid opens up and elaborates the temporal dimensions in coordination (Bardram 2000; Reddy et al. 2006) by taking into account the multiple and divergent interpretations of the past, present, and future (Emirbayer and Mische 1998), while also shedding new light on sustainable change in infrastructure research (Ciborra 2000; Henfridsson and Bygstad 2013; Tilson et al. 2010).

Implications for a Sociomaterial Perspective on Digital Coordination

Drawing on Pickering's mangle of practice, our analysis demonstrates how grid infrastructure emerges through the tensions and interplay between human and material agencies shaping ICT development and grid coordination (Edwards 1998; Edwards et al. 2007; Grisot and Vassilakopoulou 2013; Tilson et al. 2010). Our work complements recent developments in coordination theory (Bardram 2000; Chua and Yeow

Table 2. Temporally Oriented Tensions in the Coordinating of Grid Infrastructure

Coordination Dimension/ Temporally Oriented Tensions	Resource Distribution	Accountability	Predictability
Present: Accommodating and resisting grid transparency	Resource distribution is delegated to algorithms, but can result in breakdowns.	Accountability delegated to zero-codes. Error or breakdown messages render accountability (in)visible	Predictability is controlled through software codes and enhanced through monitoring practices.
Future: Modeling for grid development	Generativity of grid is a future oriented intention coordinated by software.	Future computer capacity must meet projected demand. Monitoring systems make inefficiency visible and drive future efficiency.	CRAB software models a bespoke grid with more predictable data analyses. WMS type middleware on the grid is more predictable for efficiency.
Past: Social and material inertias	The historical tiered hierarchy of high energy physics centers influences resource distribution. Historical data uses (e.g., moving large data sets infrequently) orientates current distribution pattern.	Previously trusted data sets and physical sites along with grid architecture dictate present accountability. Accountable for accommo-dating existing standards (e.g that CERN Storage manager must be supported).	Existing domain models of doing physics (e.g., that Monte Carlo techniques must be used), roles/responsi-bilities, and previous successes influence what predictions are worthy.

2010; Crowston 1997) by showing the trichordal temporal dynamics inherent in coordination processes. Specifically, we show how the interplay of habit and inertias in the past, inventiveness of actors engaged in future goal seeking, and imagined futures of technology, as well as judgment in the present, are entangled in computing grid development and use.

Table 2 highlights three coordinating tensions evident in our study, each of which dominate across the present, future, and past. Our study contributes to our understanding of coordination around accountability and predictability (Okhuysen and Bechky 2009) by furthering our understanding as to how they may be performed materially (Ribes et al. 2013).

Accommodation and Resistance of Grid Transparency in the Present

Orientated to the present, the tension of resisting (and accommodating) grid transparency can be understood in reference to *accountability* concerning who or what is responsible for which interdependent tasks, as well as *predictability* involving the ability to anticipate subsequent activity.

In our study, making responsibilities visible facilitates accountability across individuals and entities (Okhuysen and Bechky 2009) through designated user support systems such as the GGUS; similarly, material agents such as WMS send zero-codes to acknowledge submissions, rendering the responsibilities for the submission process visible, and demonstrating software accountability for job submission. Invisible responsibilities can inhibit accountability; zero-codes made accountability for job failure uncertain as they minimized transparency in the present. Abstraction and virtualization, central to the idea of grids and their efficiency (Venters and Whitley 2012), thus work to hide accountability which, in turn, can act as a form of hidden resistance. Reduced transparency led physicists to seek to improve the predictability of job success through CRAB software and the use of site monitoring practices.

Resource distribution, along with accountability and predictability, was central to understanding the temporally oriented tensions of accommodating and resisting transparency, which were negotiated in response to contingencies in the present. While resource distribution is often delegated to middleware (Foster and Kesselman 1999), existing mechanisms to minimize human commitment such as semaphores, locking, and scheduling are most suited to single processor computers (Malone and Crowston 1994). Yet the widely distributed resources of grids (Abbas 2004) require such mechanisms rethinking "from scratch" (Tanenbaum 1995, p. 34) as well as requiring considerable human commitment. Middleware, such as WMS, attempts to efficiently process multiple jobs based on current usage across the entire grid, and thus to coordinate the distribution of computation work as it is being submitted. The allocation of work is not passively produced in the present; rather, coordination involves the active configuring and performativity of the algorithm and ongoing usage of the grid by its numerous users. Human actors also demonstrate the capacity to make practical judgements among alternative trajectories of action in response to the emerging resistance, emphasizing responsiveness in the present.

Modeling Grid Development in the Future

The coordinating tension of modeling for grid development was directed toward the future. Our study shows how harnessing the generativity of digital infrastructure (Henfridsson and Bygstad 2013; Yoo et al. 2012) through the addition of new layers of software and middleware can extend and alter resource distribution. The specialists' algorithmic code, the generative features of the APIs, and, in particular, the grid's modularity enabled the ongoing purposeful improvement of resource distribution in the future.

Through digital generativity, particle physicists were able to substitute the algorithmic processes of control (e.g., delegated to WMS) to alter grid coordination. Furthermore, the social and technical embeddedness of digital infrastructure could compound this software agency by scaling up coordination through crowdfeeding scenarios where instructions are posted on the Web and subsequently widely shared. These situations and contexts confirm Kallinikos et al.'s (2013) suggestion that generativity can reduce control over digital infrastructure and their use by leaving them "accessible and modifiable by [software] other than the one governing their own behavior" (p. 357), rendering "manageability problematic" (p. 361). While computer specialists imagined a future perfected grid, the physicists imagined a successful future hump year of the LHC launch; the future is therefore manifest in the multiple imaginings of what might be possible (Kaplan and Orlikowski 2013). Furthermore, the ways in which people understand their own relationship to the future make a difference to their actions (Ribes and Finholt 2009); the physicists in our study held a positive view of future physics, one that they could help build rather than one given in the order of things.

To ensure predictability, physicists were accountable to ready the grid for analyzing CMS data and harnessed CRAB software agency to do so. The algorithmic power of white-listing maintained tight control over which sites were given computational jobs. This reflected past computing habits of physicists in harnessing software agency, especially in their use of earlier cluster computing. Future infrastructure models drew retrospectively from past computing, highlighting the interconnectedness of the temporal dimensions of coordination (Kaplan and Orlikowski 2013; Reddy et al. 2006). CRAB white-listing would ensure predictable outcomes for job submissions, and clearer accountability for analysis tasks, and was in contrast to the WMS future of generating one large, predicable virtual computer where accountability is delegated to software. Thus the CRAB and WMS software perform different grid futures. Digital infrastructure generativity shows how software agency (intertwined with human agencies in accommodation and resistance) shape future possibilities and receives impetus from the tensions and challenges of the coordination process.

Social and Material Inertias of the Past

Finally, social and material inertias such as disciplinary agency, installed bases, and conventions of practice direct the effort entailed in digital coordination toward the past. For example, the inertia of the historic hierarchy of tiered sites organized around CERN influenced where data sets and support groups were hosted, thereby directing resource distribution. Previous standards, such as CERN's CASTOR storage standard, its networking backbone, or its use of C++ programming, influenced the software agency of grid middleware. Furthermore, trusted data-sets and physical sites known to be well-run (e.g., Rutherford) were selected to receive jobs by individual users through encoded white-listing. The global structure of the grid as a hierarchy emanating from CERN therefore leads to accountability for specific users and particular data sets.

Similarly, physicists incorporated past patterns of thought and action into developing new forms of middleware to render the grid predictable. They were spurred on by the selective attention of their disciplinary agency as innovators of software agency in response to material resistance in the past , such as the moon's tidal impact, high speed trains, or discovering particles (Galison 1996). This guided their emerging actions as active harnessers of software agency, facilitated by their detailed knowledge of C++ programming.

Thus previous roles and responsibilities for accomplishing data analysis direct and organize the digital coordination process. The organizing tendencies of past experiences and memories (Mead 1932) creates stability and sustains identities (Emirbayer and Mische 1998), retaining the distinctions within and between the physicist and computer science communities and narrows the possibility for actions within particular contexts (Galison 1997). Even software agencies, such as WMS, can be considered as involving more than a routine stimulus and coordination response, as the embedded installed base roles and encoded rules dynamically interact with the context and available resources.

Following these insights we define *digital coordination* as *the temporally enacted tuning process involving multiple heterogeneous actors and across past, present, and future, where nonhuman actors are harnessed for achieving accountability and predictability in addition to resource distribution for the ongoing accomplishment of work*. This perspective sheds light on the tensions of infrastructure coordination involving "the opposing logics around centralized and distributed control" (Tilson et al. 2010, p. 754). Yoo et al. (2010, p. 732) argue that digital infrastructures are

> increasingly difficult to coordinate from a single governance point….Traditional rules and mechanisms of alignment, centralization, and cost control need to be augmented with new governance principles such as architectural models and control, software-enabled control mechanisms, new incentive mechanisms, and so on.

While we did not observe direct tussles as "ongoing contention among parties with conflicting interests" (Clark et al. 2005, p. 462) or intense rivalries among divergent interests, digital coordination led to a "constant jockeying to create preferred control points" (Tilson et al. 2010, p. 755) as coordination was negotiated by the harnessing of software agency by multiple actors.

As developed above in our perspective on digital coordination, this study contributes to our understanding of coordination around accountability and predictability (Okhuysen and Bechky 2009) by furthering our understanding as to how these organizational elements may also be performed materially (Ribes et al. 2013). In this way, we build a sociomaterial perspective of coordination processes, which to date has been largely social in orientation (Faraj and Sproull 2000; Faraj and Xiao 2006; Kellogg et al. 2006), and show how accountability and predictability can be delegated to software as part of coordinating the grid (Ribes et al. 2013). Diverse digital materialities (Barrett et al. 2012; Yoo et al. 2012) and their generative mechanisms (Henfridsson and Bygstad 2013) can powerfully distribute resources while establishing and supporting new forms of control—control that is more sociomaterial and emergent than the objectified intentions within digital technology (Kallinikos 2005) often implied in the existing literature. Our perspective on coordination also builds a novel approach to temporality and a more dynamic perspective on sustainable change in digital infrastructure, which we discuss below.

Temporality and the Challenge of Sustainable Change in Digital Infrastructure

Our study contributes to the neglected area of temporality in ICT infrastructure research (Karasti et al. 2010; Ribes and Finholt 2009) and thereby provides new insight into how infrastructure changes in a sustainable manner. The layered nature of digital technology supports high levels of generativity (Yoo et al. 2010; Zittrain 2006) in that software can be used for multiple services and can be harnessed in different ways so that "unprompted change driven by large, varied, and uncoordinated audiences" is produced (Zittrain 2006, p. 1980). In our case, WLCG middleware was fluid and open to new ways of being harnessed, yet these changes were conditioned by past inertias and future intentions. Building on Yoo et al.'s (2010, p. 730) insight that "the greater the heterogeneity, the more generative the platform becomes," we highlight that a greater heterogeneous range of agents—for example more e-science groups being involved in the grid use—will enable more generative possibilities since there is greater diversity of past inertias constraining the status quo, as well as more future goals. Yet these generative possibilities may be counterproductive to one subset of agents as the evolving generative features may work against their own need to respond to the contingencies and demands of the present. Our temporally embedded perspective of generativity reveals the dynamic relationships, rather than discrete entities, accomplishing ongoing change to infrastructure.

The sustainability challenge emerges between current users, orientated to more immediate and short-term work projects, and technology developers tasked with developing an infrastructure that is sustainable for decades (Karasti et al. 2010; Ribes and Finholt 2009; Star and Ruhleder 1996). In understanding this challenge, the future has been conceived of as the long now (Brand and Brockman 1998; Ribes and Finholt 2009), so as to "achieve persistent institutional arrangements" and "persistent human arrangements" (Ribes and Finholt 2009, p. 379). Defining the desired future in terms of the present and past leads to an essentially static notion of sustainability where the present persists through time.

Our trichordal temporal approach emphasizes the dynamic—rather than stable—aspects of digital infrastructure as a means of understanding sustainability and change. We show that the social and material agencies enacting digital infrastructure are orientated to multiple dimensions of time in a dynamic interplay, although one temporal dimension may be dominant in directing a particular action (Emirbayer and Mische 1998). Our findings reveal how future plans for a sustainable infrastructure are sociomaterially disciplined by the past as well as being revised in the emerging present.

Rather than a focus on sustainable design as the bedrock of the long now of infrastructure time (Karasti et al. 2010; Ribes and Finholt 2009) our findings support the more dynamic notion of growing infrastructure (Edwards et al. 2007). Yet we would suggest that such growth is akin to the dance of agency that cultivates an orchard of bonsai trees through creative pruning and adaptive grafting rather than the clearly imposed design and sculptured form of topiaries (Pickering 2013). The verb *infrastructuring* (Bietz et al. 2010; Star and Bowker 2002) emphasizes the relational nature of infrastructure which is "not simply a 'substrate' upon which something 'runs.' Rather, it establishes and sustains particular types of relations and actions, while disabling others" (Ribes et al. 2013, p. 4, citing Star and Ruhleder 1996). For example, in our study, as physicists harness CRAB and other middleware code that could over-ride the WMS, they were configuring a new, yet sustainable, future grid infrastructure, although one which would be more bespoke to the needs of particle physics and the discovery of new physics.

Our study highlights that digital infrastructure is not just a potential support for coordinated work (Bardram 2000), or interconnected within the performance of coordination (Constantinides and Barrett 2012). Instead, as called for by Constantinides and Barrett (2012), our research provides a sociomaterial understanding of coordination, whereby a sociomaterial future and past are accounted for within coordination. For practitioners, this may lead to a broader analysis of the influence of their innovations as grids reconfigure scientists' work and communications (Ribes et al. 2013).

For practitioners seeking to innovate digital infrastructures such as grids, our research highlights the importance of understanding coordination as more than a technical automation challenge (Bird et al. 2009). If, as some believe, grid architectures come to dominate large-scale computing (Gray 2013) and cloud computing (Venters and Whitley 2012), then this study shows that innovating these new services will involve navigating what Hendfridsson and Yoo (2013) recently described as a "borderland between past and future…[a] twilight zone of innovation" (p. 2). Yet in contrast to their implication of an innovation trajectory led by the agency of the innovator, our study shows that, for digital infrastructure innovation, practitioners must be aware of the legacy of technology and human practices that provide a past-focused drag on their innovation efforts, and similarly must remain attuned to how imagined technology futures and future intentions create inertia. Henfridsson and Yoo suggested that "familiar trajectories and associated practices" (p. 4) put at risk attempts to innovate a different future. Our research elaborates this, showing that legacy of scientific practice, previous technology experiences (e.g., around cluster computing), and past technology standards (e.g., TCP/IP, Linux, and CASTOR) alter such trajectories, and will define their rhythm (Ribes et al. 2013) and direction. Similarly, imagined futures of developing technology trajectories—including future digital standards and Moore's law, imagined work practices (e.g., LHC analysis), and individual intentions—influence coordination. For practitioners, then, an intimate knowledge of the past, and imagination of the future, may be central to their success in innovation (Battilana et al. 2009).

Yet these sociomaterial influences are different for different groups of agents, and it is the interaction of these which shapes the contours of possible futures (Pickering 1993) for the coordinated digital infrastructure. Indeed, a primary aim of grid computing is the sharing of the infrastructure among multiple sciences and communities (Foster and Kesselman 2004b), so extending such understanding of past and future to the different groups involved is likely vital.

Finally, this study shows the necessity of better understanding how technical and social arrangements are entangled in practices of coordination. While our case study of the LHC grid is clearly a special case, coordination is commonplace in digital infrastructures (Venters and Whitley 2012) although little researched. Facebook harnesses both human and material agency to coordinate tens of thousands of globally distributed IT resources[6] and understanding such services will require studying their coordination as influenced by past and future. Indeed Moore's law was not merely a mapping of the past and future of semiconductors, but agential in the trajectory of semiconductors in part though Moore's position as executive vice-president of Intel driving the pace of their innovation based on inertia of the past. Similarly our study shows that past and future have agency on the present coordination of digital infrastructure and must be better understood. We believe our sociomaterial approach provides a valuable starting point for future studies on digital infrastructures and their coordination.

Conclusion

This paper develops a sociomaterial perspective to grid coordination that extends Pickering's mangle of practice to account for a trichordal temporal approach in the dance of

[6]Htp://www.datacenterknowledge.com/the-facebook-data-center-faq/.

agency. Our perspective highlights the tensions that emerge in digital coordination related to material and human elements of resource distribution, accountability, and predictability, as dynamic emergent relations by which the past and intended future shape present coordination practices. We not only recognize the material agency of the IT artefact but also emphasize the inner workings of different materialities such as APIs, middleware, and software code in coordinating the grid. Thus a key to grasping the dynamic possibilities of digital coordination is to view it as composed of variable and changing orientations within the flow of time, wherein multiple tensions shape interactions between actors, material agencies, and ongoing grid performance. Furthermore we show how the emerging tensions can extend our understanding of change in digital infrastructure development and evolution (Ribes and Finholt 2009; Tilson et al. 2010).

Our second contribution informs the increasingly important research area of temporality in infrastructure (Ribes and Lee 2010). We shift the infrastructure debate around sustainable change toward a dynamic interplay of generative material and social agencies, oriented to multiple dimensions of time. Thus, in addition to a consideration of a long now, projected futures and inertias of the past are also enacted within the ongoing development and use of digital infrastructure. Our findings caution against an over reliance on a rules based approach to coordination involving either the harnessing of the software or human agency because of the grid's indeterminacy and non-repeatability. The diversity of values and principles embedded within infrastructure are incommensurable, and hence a concern for situated grid coordination, rather than a universal application of rules, will be more productive.

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