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The Lure of the Virtual

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Although organizational scholars have begun to study virtual work, they have yet to fully grapple with its diversity. We draw on semiotics to distinguish among three types of virtual work (virtual teams, remote control, and simulations) based on what it is that a technology makes virtual and whether work is done *with or on*, *through*, or *within* representations. Of the three types, simulations have been least studied, yet they have the greatest potential to change work's historically tight coupling to physical objects. Through a case study of an automobile manufacturer, we show how digital simulation technologies prompted a shift from symbolic to iconic representation of vehicle performance. The increasing verisimilitude of iconic simulation models altered workers' dependence on each other and on physical objects, leading management to confound operating *within* representations with operating *with or on* representations. With this mistaken understanding, and lured by the virtual, managers organized simulation work in virtual teams, thereby distancing workers from the physical referents of their models and making it difficult to empirically validate models. From this case study, we draw implications for the study of virtual work by examining how changes to work organization vary by type of virtual work.

Key words: organizing for innovation; technological change; product design; virtual work; simulation; representation; digitization; semiotics
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Introduction

Since the earliest days of the computer revolution, the lure of the virtual has seduced thinkers, writers, designers, and others with the idea that we might someday accomplish with computers that which we have historically done only physically, thereby potentially allowing us to dispense with the physical. Although the idea of virtuality still attains its zenith only in science fiction, computer scientists have long sought to program virtual worlds, and since the 1990s, they have had considerable success, especially in video gaming (Tschang 2007). Yet virtuality has moved well beyond games. Sophisticated graphical simulations are now used to train aircraft pilots, soldiers, and emergency responders, among others (Kincaid et al. 2003, Macedonia 2002, Longridge et al. 2001). Teams now routinely communicate and coordinate via e-mail, instant messaging, and Web-conferencing applications without ever meeting in person (Maznevski and Chudoba 2000). Doctors operate on patients and military personnel control drone aircraft from as much as a half a world away using digital video images and other real-time data collected by sensors (Drew 2009, Marescaux and Rubino 2004, Satava 1995). With continued innovation in digital technologies, the possibility of working virtually is moving from the realm of science fiction to the everyday reality of the workplace.

As these examples suggest, exactly what "working virtually" means varies widely. Although students of work and organizing have begun to study virtual work, they have yet to grapple with its diversity. The implications of virtual work for organizing are likely to vary with the physical phenomena that technology digitizes as well as with the relation between those phenomena and the representations that technology creates. The latter are particularly important because virtuality typically implies working with a representation of the physical rather than with the physical itself. It is along these lines that we distinguish digitization from virtuality. Digitization involves the creation of computer-based representations of physical phenomena. Because these representations can traverse long distances via computer and telecommunications links, digitization facilitates separation between people and the represented phenomena (physical objects, physical processes, or other people). Virtuality occurs when digital representations stand for, and in some cases completely substitute for, the physical objects, processes, or people they represent.

By representation, we mean what semioticians call a sign: something that stands for something else within the bounds of a particular speech community, culture, or community of practice (Eco 1979). According to Saussure (1916/1966), signs are composed of two elements: a signifier (such as a word, an image, a number, or a sound) and the signified (that which the sign denotes or connotes). Frege's (1892/1980) distinction between meaning and reference is one useful way to classify signs. Some signs have both a meaning and a referent: they enable interpretation among those who know how to read them (meaning) and also point to something definite in the world, a physical entity (referent). For example, a blip on a sonar screen signifies the presence of a submarine, a fish, or another object in the water. If it did not, the blip would be instrumentally useless because it would have no referent, although it could still have meaning, perhaps as the functional equivalent of a lava lamp.

Other signs have meaning but no referents (Quine 1961). Consider numbers in a spreadsheet signifying the worth of houses in a local market. As concepts within the context of the spreadsheet, the numbers clearly have meaning. Residents of the community might see them as an estimate of the amount of money they can expect if they sold their homes. Sociologists might see them as evidence that a neighborhood is becoming tonier or less tony. Indeed, numerous meanings are plausible, but under no circumstances do the numbers refer ostensively to houses. One could not pull a number from the spreadsheet, write it on a piece of paper, and know which house had that worth, because the number itself could stand for anything. One could, however, pull the address of a house from the spreadsheet, write it on a piece of paper, and find the house. This is because an address is a signifier that refers.

A useful way of further differentiating among representations that have referents is to consider the nature of the signifier's relationship to the signified. Peirce's (1932) taxonomy of *indices*, *icons*, and *symbols* takes this approach. Indices are signs that have a physical and existential relationship to that which they signify. An index usually co-occurs with and is often produced by that which it signifies. Classic examples include smoke as a sign of fire, vapor trails as evidence of a passing jet, or our ability to identify individuals by the sound of their voice.

Icons are signs that signify because they closely resemble that which they signify. Typically, icons consist of visual images such as pictures and portraits. Architects, engineers, scientists, and members of other occupations have long depicted the structure of objects using iconic representations. Sketches, blueprints, and computer-aided design (CAD) drawings are well-known examples. The desktop on your computer is likely to be full of icons, albeit not very sophisticated ones. For instance, you likely delete files by dragging and dropping them into an iconic trash can.

Unlike indices and icons, symbols signify entirely by cultural convention; the link between signifier and signified is essentially arbitrary. On a flowchart of a production process, for example, a rectangle may represent a machine, but the machine itself may not be rectangular in shape. We come to understand that the rectangle represents the machine because a legend on the flowchart tells us so or because standard practice in an industry is to represent machines by rectangles. The rectangle provides no clue as to the appearance of the machine.

In this paper, we first draw on semiotics to develop a taxonomy of virtual work by distinguishing among three types of virtual work—virtual teams, remote control, and simulations—based on aspects of digitization, representation, and virtuality. Students of organizing have attended to the first two types but have largely ignored the last (a few notable exceptions include Boland et al. 2007, Dodgson et al. 2007, Thomke 2003). Yet simulations are incredibly important because it is with simulation that virtuality comes closest to substituting for reality. Simulation, therefore, has the greatest potential to change work's historically tight coupling to the physical and, with it, the work relations of people to objects and to each other. Through a case study of an automobile manufacturer, we show how innovation in digital technologies and the increasing verisimilitude of iconic representations in simulation affected workers' dependence on physical objects and on each other. Ultimately, we show how management's failure to distinguish between types of virtual work blinded it to new organizational dependencies, thereby causing problems in the execution of work. From this case study, we draw larger implications for the study of virtual work.

Types of Virtual Work

Virtual Teams: Operating with or on Representations

The first and most widely discussed type of virtual work in organization studies pertains to geographically distributed teams. Although students of "virtual teams" have used the term to gloss a host of phenomena, ranging from coordinating across time zones to managing the cultural diversity of team members, all definitions pivot on the idea that teammates are spatially separated from one another; thus, they must work together without face-to-face contact, typically via digital technologies that mediate communication (Griffith et al. 2003, Gibson and Gibbs 2006). For this reason, virtual teams substantially change how work is organized.

From a semiotic point of view, e-mail, instant messaging, and other digital communication technologies facilitate new forms of work organization by enabling people to interact with indices of each other. Voices on telephones, the text of an e-mail, or a cursor moving over an image displayed via a Web-conferencing tool stand for the other person because the voice, the typing, or the moving cursor are indices of a person in precisely the way that a vapor trail signifies the passing of a jet plane. Indexical representations thus render people on geographically distributed teams virtual. Team members *operate with* these representations; for example, they read e-mails and respond to them as a way of conversing with distant colleagues whom they cannot engage in face-to-face conversations.

Like many white-collar workers, members of virtual teams also *operate on* representations, in the sense of crafting or manipulating them. In these cases, the representations are typically not indices of people but symbolic or iconic representations that are themselves the objects of work. Tasks that involve operating on representations are commonplace—for example, writing a report in a word processor, calculating a budget with a spreadsheet application, or drawing a building using CAD software. In some occupations, the representations on which people operate have both a meaning and a referent. Such is the case with CAD, where the drawing stands for an object that either already exists or that will be built using the drawing as a guide. In other occupations and tasks, the representations on which people work have a meaning but no referent. When operating on representations that have no referent, workers may craft messages or change perceptions, but their manipulations do not directly affect physical phenomena. Consider, for example, a distributed team of real estate analysts working with spreadsheets that document the houses for sale in local markets. The analysts can manipulate the numbers in the spreadsheets to make the markets look hotter, which in theory should induce some homeowners to sell their homes. But no matter how the analysts change the spreadsheets, they will not directly and immediately cause "for sale" signs to appear in neighborhood yards.

Work that involves operating on digital representations without referents is highly portable and, thus, lends itself to execution by virtual teams: because the representations are digital, they can be easily transmitted from one location to another via e-mail or websites. Moreover, because the representations are not referentially tied to a physical entity, their meaning is free of physical (although perhaps not cultural) context. Virtual teams were not, however, the impetus for the creation of such representations; these exist even when members of colocated teams work with computer applications. The advent of virtual teams, therefore, altered teammates' physical access to one another, but it did not change how team members worked with many of the representations generated in the course of everyday tasks.

Nor did the advent of virtual teams necessarily change people's roles. Managers often form virtual teams because they require the expertise of a distant individual (Boh et al. 2007, Sole and Edmondson 2002). For example, a team may turn to an individual in a different country to acquire expertise with a particular market. In joining the team, the marketer would not usually assume new duties outside or inside the realm of marketing simply because she was now working virtually. Rather, she would carry out her role and its associated tasks as before; the only difference would lie in her collaborating with teammates via indices rather than in person.

Two decades of research on virtual teams tells us that members experience a variety of problems precisely because digitally mediated contact forces them to interact via indices. Establishing trust through indices seems particularly difficult; absent trust, people are less likely to share information (Kanawattanachai and Yoo 2002, Jarvenpaa and Leidner 1999). The problem, as Handy (1995, p. 46) contended, is that "trust needs touch." Virtual teams also often struggle with the mechanics of getting work done, especially when tasks are interdependent. In general, task interdependence requires frequent coordination (Faraj and Sproull 2000), which is difficult for virtual teams because members have trouble gaining access to the individuals and information on which they depend. Numerous studies show that distant others routinely fail to respond to team members' messages (Cramton 2001) and that sometimes they fail to provide access to critical data (Levina and Vaast 2008, Metiu 2006). Coordination can also be difficult because team members must work across time zones and cultures and because the communication technologies they use may foster incomplete messages, misunderstandings, and conflict (Maznevski and Chudoba 2000, Hinds and Bailey 2003, Sproull and Kiesler 1991). Yet despite these problems, organizations have continued to be lured by the idea that people can work just as effectively on virtual teams as on colocated teams.

Remote Control: Operating Through Representations

A second type of virtual work involves digital technologies that mediate our relations with objects rather than people. For example, operators in continuous process plants, such as paper mills and oil refineries, use data collected from sensors located throughout the plant to issue commands from computer terminals to activate effectors that change how the machines are working, all from a control room located away from the actual factory floor. Similarly, engineers at the Jet Propulsion Laboratory monitored and operated the rover that NASA placed on Mars via digital interfaces and commands. Firemen increasingly use robots to search for victims in burning buildings.

In such cases, people operate with data collected by a physical system and with digital representations of the system's functioning to change the system's behavior. As with virtual teams, digitization has enabled spatial separation, but in this case, people are separated from objects rather than other people. Instead of a digital communication system as employed by virtual teams, here the technology is a complex cybernetic network of digital sensors, digital control algorithms, digital state representations, and digitally activated effectors. With this technology, workers can remotely manipulate objects that were formerly amenable to only direct haptic control.

People whose work entails controlling objects remotely are best thought of as *operating through* rather than with or on representations. In such work the goal is to directly and immediately affect the representation's referent. Historically, the idea that manipulating a signifier could affect the signified was tantamount to magic, as in the case of sticking pins in a voodoo doll to incapacitate an enemy. Today, remote control is becoming increasingly prevalent as digital technologies for sensing and processing physical properties advance. The representations through which people operate remotely on physical systems are likely to be either symbolic (if information were displayed as, say, numbers, colors, or shapes) or iconic (if the information were displayed as real-time pictures of processes).

Even though remote control is far from uncommon, it has attracted less attention among students of work and organizing than have virtual teams. One reason may be that remote control typically occurs in technical or manufacturing contexts, and organizational studies of such workplaces have declined since the demise of industrial sociology. There is some evidence, however, that manipulating physical objects through digital interfaces prompts changes in the organization of work, alters the way people make sense of—and come to trust—the objects with which they work, and transforms workers' roles.

Studies of paper mills have documented this transformation. Before the introduction of computerized information systems, operators relied on their senses when interacting with machines and materials to gain information about the production process (Vallas and Beck 1996, Zuboff 1988). For example, operators judged moisture content by running their hands over rolls of paper and looked for weight variation by banging wooden sticks on the finished product. They came to trust that which they could sense directly.

With the advent of remote control, workers were relocated to air-conditioned control rooms away from the towering, loud machines that had populated their workplace. The isolation was figurative as well as literal: it placed analytical distance between the operators and the objects that had previously served as the source of their knowledge and understanding. Now, operators needed to analyze information displayed on digital interfaces as diagrams, maps, and graphs that served as symbols and icons of the production process. In documenting operators' struggles to come to terms with the demands of this new "informated work," Zuboff (1988) reported that workers had to resist the temptation to leave the control room to check production equipment. Operators had to learn instead to trust the information displayed on the interfaces as accurate representations of what was happening on the floor.

These findings from paper mills resonate with studies of nuclear power plants, a second context in which work with virtual objects has attracted scrutiny. Perrow (1983, 1999) and Hirschhorn (1984) argued that working virtually with a complex, tightly coupled, technical system not only increases an operator's cognitive load, but also requires different forms of organizing precisely because complicated representational interfaces change the nature of an operator's work. For this reason, Perrow (1983) counseled that organizations should pay more attention to the work of industrial engineers, psychologists, and computer scientists who study the physical, cognitive, and social demands of working with digitized control systems. Unfortunately, Perrow's counsel is rarely heeded when organizations find themselves drawn to the lure of the virtual in the form of remote control. Indeed, studies of paper mills indicate that organizations are rarely willing to consider how operating through representations might require further changes in the organization of work and patterns of dependency—in part, because doing so would require managers to abdicate at least some of their power and authority to operators (Vallas and Beck 1996, Zuboff 1988).

Simulations: Operating Within Representations

A third type of virtual work also entails an altered relationship between representations and physical entities, but it goes well beyond remote control. Rather than merely mediating relationships with objects or people, some new digital technologies promise, if only temporarily, to eliminate the need for a connection altogether. Importantly, most simulation technologies not only represent physical entities, but they also emulate physical processes and, for this reason, move us closer to the notion of virtuality envisioned by science fiction writers and computer scientists.

Advanced simulations, which use computational, visualization, and modeling software to represent objects or people iconically, are often of this sort. Doctors in medical schools increasingly use computer simulations of the body to teach anatomy, dissection, and surgery in lieu of actual cadavers or patients (Prentice 2005, Csordas 2001). Architect Frank Gehry used iconic representations in design that were "complete digital prototype[s] of a building that [act] like the actual building" (Boland et al. 2007, p. 636). Fire engineers use simulations to study how fire and smoke will move through, and how people are likely to evacuate, a building (Dodgson et al. 2007).

In these cases, virtual no longer means working with distant objects or people via representations that stand for them: it means working solely with representations that substitute for the object or person.

When workers substitute digital simulations for objects or people, they no longer simply operate with, on, or even through representations. They begin to *operate within* them. Operating within a representation means that the worker's connection to the referent is suspended. The presumption is that what we learn from simulating is equivalent to what we would have learned had we experimented with the physical object or person being simulated. Another way of putting it is that we take a model of the phenomenon to be an adequate facsimile of the phenomenon itself.

Writing before the widespread diffusion of computers, the philosopher Max Black (1962, p. 222) defined a model as a "material object, system or process designed to reproduce as faithfully as possible in some new medium the structure or web of relationships in an original." Because models are referential, Black argued, they are useful for helping us develop hypotheses about the phenomena that the model signifies. Yet precisely because models are referential, working with them carries an inherent danger, a danger that grows as the model's verisimilitude increases: mistaking the behavior of the model for the behavior of its referent. Black commented (1962),

> The remarkable fact that the same pattern of relationships, the same structure, can be embodied in an endless variety of different media makes a powerful and a dangerous thing of the ... model. The risks of fallacious inference from inevitable irrelevancies and distortions in the model are now present in aggravated measure. Any would-be scientific use of a ... model demands independent confirmation.... Models furnish plausible hypotheses, not proof.... The drastic simplifications demanded for success of the mathematical analysis entail a serious risk of confusing accuracy of the mathematics with strength of empirical verification in the original field. Especially important is it to remember that the mathematical treatment furnishes no *explanations*. Mathematics can be expected to do no more than draw consequences from the original empirical assumptions. (pp. 222–225, italics in original)

Engineers who design and use simulations voice similar warnings when distinguishing between verification and validation (Cunningham 2007, Kurowski 2008). Verification entails checking the assumptions behind and the implementation of the equations, parameters, and algorithms that comprise a mathematical model. By validation, engineers mean checking a simulation's predictions empirically against reality—namely, the performance of the actual objects under the conditions being modeled.

Thornton (2010) interviewed numerous mechanical engineers who specialized in finite element analysis (FEA), a sophisticated mathematical method for simulating how objects respond to kinetic force, friction, wind shear, loads, and other types of stress or strain. Thornton's engineers consistently reported that inadequate validation is the most common problem with simulation analysis. Thornton (2010, p. 42) wrote,

> The biggest challenge in FEA is validation, carefully chosen and closely monitored physical tests that confirm whether or not physical reality and virtual reality line up. A consensus among FEA analysts is that validation ensures there are no hidden disconnects between the model and the physical testing, that correct physical properties are used and that properties are analyzed accurately based on correct principles of physics.

The two most common reasons cited by Thornton's engineers for inadequately validated models were engineers inexperienced with the intricacies of simulation and managers whose desire to cut costs leads them to assume that simulations are sufficient evidence. As one of Thornton's informants put it, "Too many engineering managers *do not understand the vast complexity* of the physical world that FEA addresses.... Any mechanism that allows developers to reduce the cost and time for product or process development is being seized upon by engineering managers" (2010, p. 41, emphasis added).

Trusting simulations to the point of mistaking them as complete substitutes for reality is not limited to engineering managers who are under pressure to cut costs. Turkle (2009) described how students believed too readily in the computer simulations of natural processes and experiments they viewed in physics and chemistry classes: "When students claimed to be 'seeing it *actually* happen' on a screen, their teachers were upset by how a representation had taken on unjustified authority" (p. 29, italics in original). The verisimilitude of iconic representations on computer screens prompted one professor to constantly remind his students that "simulations are not the real world.... There is no substitute for knowing what a kilogram feels like or knowing what a centimeter is or a one-meter beach ball" (Turkle 2009, p. 30). Such reminders were important because students had to learn that simulations could only match reality if the models were consistently validated against data obtained from the real world.

Table 1 summarizes the three types of virtual work in terms of digitization, representations, and virtuality. Table 2, which shows changes in work that arise in the context of virtual work for each of the three types, makes clear the gaps in our knowledge about changes in work organization as well as tasks and roles under simulation. In addition, although Table 1 indicates that digitization in simulation permits spatial separation between people and objects or other people, Table 2 points out problems in model validation and excessive trust in models that speak against the logic of such separation.

In the remainder of this paper, we explore how the development of increasingly iconic simulations gradually altered the organization of engineering in a large

Table 1 Digitization, Representations, and Virtuality by Type of Virtual Work

	Type of virtual work		
	Virtual team	Remote control	Simulation
Digitization			
Purpose of digitization	Mediated communication	Mediated operation	Emulated operation
Technology	Communication systems	Complex cybernetic networks	Computational, visualization, and modeling software
Spatial separation	Between team members	Between people and objects	Between people and objects or other people
Representations			
Workers' relationship to representations	Operating with or on	Operating through	Operating within
Common types of representations	With referents: Voices on telephone, e-mail, CAD drawings Without referents: Budgets, reports	With referents: Flowcharts, displays, diagrams, maps, graphs	With referents: Models, animations
Manipulation affects referent?	No	Yes	No
Virtuality			
Purpose of virtuality	Distant collaboration	Distant control	Study and experimentation
Physical entity made virtual	People	Object	Object or people
Interaction between physical and virtual	People interact with one another via indexical representations that stand for the team members	People interact with existing physical objects via symbolic and iconic representations that stand for the objects and their associated processes	People work with primarily iconic representations that substitute for physical entities (existing or future) and their associated processes
Examples	Distributed team of real estate agents	Paper mills, oil refineries, nuclear power plants	Medical education, building design, new product development

automobile company, as well as the tasks and roles of engineers. As the simulations' representations became more iconic and realistic, managers' failure to appreciate the subtle relationship between the sign and referent led them to confuse the act of operating *within* representations with the act of operating *with or on* representations. As a result, they came to believe that operating within representations was a form of work amenable to virtual teams because they saw little need for access to physical vehicles. By assigning simulation work to virtual teams, managers organized work and assigned tasks and roles in ways that unwittingly broke the link between icons and referents (and, hence, the ability to validate models), thereby creating difficulties.

Table 2 Changes in Work Organization by Type of Virtual Work

	Type of virtual work		
Changes in work organization	Virtual team	Remote control	Simulation
Work structure	Interdependent workers placed on teams with members distributed geographically	Workers colocated with each other, computers, and controls beyond the immediate vicinity of production machines	?
Tasks and roles	Few or no changes	Increased analytics, "informated" work, workers equipped for decision making	?
Related problems	Lack of trust among team members, misunderstanding of indexical communication, coordination mishaps	Lack of trust in representations, cognitive overload	Excessive trust in models, difficulty validating models

Methods

Research Design

International Automobile Corporation (IAC, a pseudonym), headquartered in the United States, was the setting for our study. Although the majority of IAC's engineering workforce resided at its technical center in Michigan, IAC had long maintained engineering operations abroad. In 2003, IAC opened a new center in Bangalore, India to provide digital engineering services to IAC's other engineering centers. Unlike IAC's other centers, Bangalore had no physical testing facilities; the workforce only provided math-based analyses and assisted with setting up simulations. In fact, management purposefully created the India center as a step toward its goal of completely replacing physical tests with virtual ones. The decision to locate in Bangalore was telling. With its large information technology infrastructure, Bangalore was the offshoring, but not the automotive, capital of India (Chaminade and Vang 2008). We focused on IAC's U.S. center and its interactions with the India center. At the U.S. center, we studied engineers involved in product design, physical testing, and simulation. Because there were no engineers in product design or physical testing in India, we only studied Indian engineers who did simulations.

Data Collection

We collected data between July 2003 and July 2006 primarily through ethnographic observation of, and informal interviews with, engineers at work. At the U.S. center, we observed 10 engineers in physical testing, 7 engineers in product design, and 17 engineers in simulation. In general, we observed each of these engineers on four separate occasions. In addition, we conducted 11 semistructured interviews at the U.S. center with engineers, engineering managers, and individuals who managed, purchased, or developed the technologies that the engineers used. Because many of the American engineers and managers had considerable tenure with IAC, our conversations and interviews covered not only on the way work was currently done but how it was done and organized in the past. By combining such recollections with documents from earlier years, we were able to construct a history of how design and performance analysis had evolved at IAC. We observed 11 engineers in Bangalore. Because we observed most Indian engineers on fewer occasions than we did engineers in the United States (typically twice), we conducted half-hour semistructured interviews with each Indian engineer that we observed. We complemented these interviews with 20 interviews of other Indian engineers and managers. Interviews at both sites were audiotaped and transcribed. Altogether, we observed engineers at work on 163 occasions.

Data collection spanned two countries and took three years to complete. Over this time, 18 individuals worked on the research: 2 faculty members, 3 graduate students, 3 undergraduate students, and 10 IAC research and development staff. Although single researchers carry out most qualitative field studies, some studies have used teams and were, therefore, useful as we designed our research (Barley 1996, Miles 1979). Specifically, they taught us that we would need to develop specific techniques to ensure consistency in how team members recorded data.

In addition to taking running notes on the engineer's interactions with technologies, people, and documents, we audiotaped conversations when we could not keep pace by writing notes or when discussions became very technical. When our informants worked at computers, we requested screenshots of software interfaces and digital copies of the models, e-mail, and documents with which they worked. Each day, we photocopied key documents that the engineers had used, including drawings, sketches, pages from brochures, handwritten calculations, and scraps of paper on which they had scribbled notes.

Collecting so many types of data enabled us to prepare field notes that described actions, conversations, and visual images simultaneously and, thus, to produce a record not only of what engineers did and said but also of what they worked with and created. The first step in assembling a day's field notes was to expand the running notes taken in the field into full narratives that someone who had not been on-site could understand. We transcribed tapes directly into the body of this narrative at the point where the talk occurred. Similarly, we indexed screenshots and photocopies of documents at the point in the field notes where they were used. Weaving together actions, conversations, and images allowed us to capture and better understand an engineer's gestures, movements, and, especially, the referents of indexical speech (e.g., "Here, you see ..." or "Right here, we need ..."). We wrote appendices for each day's field notes that described the documents we collected and, if the document was the result of the engineer's work, how it evolved. These descriptions also covered how and why the engineer used the document. Completing a full narrative of a day's observation took between two and two and a half days.

Data Analysis

Whereas the entire research team was engaged in data collection activities, only the authors performed data analysis. Following Yin (1994), we organized our analysis around the motivation for our study—namely, determining what happens when new digital technologies facilitate operating with, on, and within representations of physical entities, as well as the transmission of these representations across great distances.[1] We paid particular attention to how engineers understood and managed the relationship between digital representations and their physical referents as well as to the organization of work both within and between the two sites we studied over time.

Beginning with a within-case analysis (Miles and Huberman 1994), we first examined the U.S. center and built separate narratives for each engineering role: product design engineers, physical testing engineers, and simulation engineers. For each role we documented work tasks and constructed a narrative of its history at IAC. We paid attention to how engineers in each role interacted with and used physical parts. Because simulation represents the substitution of the representation for the referent, we particularly noted engineers' access to, and dependence on, these objects as we considered work structure. We paid similar attention to engineers' interactions with, dependence on, and access to peers in other roles. We conducted multiple readings of our field notes and interview transcripts, refining our narratives in the face of supporting or disconfirming evidence for our developing ideas. We next built the same kind of narrative for the simulation engineers at the India center.

Finally, we turned to cross-case analysis, looking for differences across the engineering centers (Miles and Huberman 1994). Our focus in this step was primarily on the simulation engineers because the India center did not have the other roles. We paid particular attention to how, and if, simulation engineers at both sites validated their models. We contrasted and compared the engineers' access to and dependence on physical objects. For the India center, we specifically explored how engineers handled their limited access to objects.

Because the historical narrative of the various occupations was strongly influenced by the adoption of new digital technologies, we organized our results by the sequence in which engineering at IAC adopted CAD, FEA, and computer-mediated communication (CMC) technologies. We explain how work was divided across engineering roles in each period, how each new technology offered new representations (symbolic, iconic, or indexical) of objects or people, how management's belief that one could separate simulation's representations from their referents led to the global distribution of this work, and how this change eventually led to an array of problems.

Changes in Technology, Work Organization, and Representations at IAC

Distinct historical periods, each associated with the deployment of a new technology, punctuated the process by which the organization of work at IAC changed over time. We begin by describing the situation before the arrival of CAD (Period 1). We then describe what occurred when IAC adopted CAD in engineering design (Period 2), what transpired when FEA was deployed for engineering analysis (Period 3), and finally what took place after IAC used CMC technologies to offshore simulation work to India (Period 4). For each period we document how roles, tasks, and engineers' dependence on and access to objects and people changed.

Period 1: Pre-Digital

Before CAD arrived, IAC's engineering division designed vehicle parts, produced blueprints of those parts, and analyzed how vehicles performed using physical tests. Under the division of labor during this period, parts engineers designed parts and oversaw the building of prototypes. Drafters drew the blueprints for the parts. Test engineers assessed the actual performance of parts and vehicles. Modelers in the research and development (R&D) division were responsible for analyzing vehicle performance with primitive mathematical models. Table 3 summarizes the allocation of tasks, the engineers' dependence on and access to physical parts, and interdependencies over time for engineering and R&D.

The top panel of Table 3 (Period 1) reveals that before the arrival of CAD, all roles in engineering depended heavily on and had good access to vehicle parts. Test engineers had the best access. They split their time among teardown rooms for inspecting disassembled vehicles and experimental bays for studying vibration and other phenomena. They also test drove vehicles on a racetrack at IAC's proving grounds 30 miles away. Parts engineers and drafters, all of whom operated on blueprints of physical objects, were separated from the test engineers in another building on IAC's main campus. As a result, their access to parts and vehicles was slightly limited. Nevertheless, parts engineers and drafters kept key vehicle parts in their cubicles, and when they needed better access, they went to the test facilities to witness physical tests or to inspect parts before or after testing.

The three engineering occupations not only depended on access to parts, but they also depended heavily on each other and were sufficiently close to each other to interact face to face. Parts engineers needed drafters' drawings to negotiate with suppliers, manufacturing staff, and other engineering groups; they used test engineers' results to modify designs when parts failed. Drafters relied on parts engineers to set drawing specifications. Test engineers depended on parts engineers to have parts built to specifications to ensure valid tests.

Figure 1 illustrates the physical objects and the representations that IAC engineers used to design parts and study performance over time. The top panel pertains to designing vehicle parts; the bottom panel pertains to analyzing vehicle performance. Said differently, the top panel displays representations of structure, whereas the bottom panel displays representations of functioning or process. Before CAD, parts engineers and drafters used physical vehicle parts (such as the actual engine

Table 3 Work Organization and Technology in Engineering and R&D at IAC by Period

Division	Engineering			R&D
Period 1: Pre-digital				
Role	Parts engineer	Drafter	Test engineer	Modeler
Task	Design of parts	Drawing of parts	Performance analysis (physical)	Performance analysis (math)
Dependence on physical parts	High	High	High	Low
Access to physical parts	Moderate	Moderate	High	Low
Task interdependence across roles	High within engineering, low across engineering and R&D			
Access to individuals in other roles	Moderate			

Period 2: Computer-aided design arrives			
Role	Design engineer	Test engineer	Modeler
Task	Design and drawing of parts	Performance analysis (physical)	Performance analysis (math)
Dependence on physical parts	High	High	Low
Access to physical parts	Moderate	High	Low
Task interdependence across roles	High within engineering, low across engineering and R&D		
Access to individuals in other roles	Moderate		

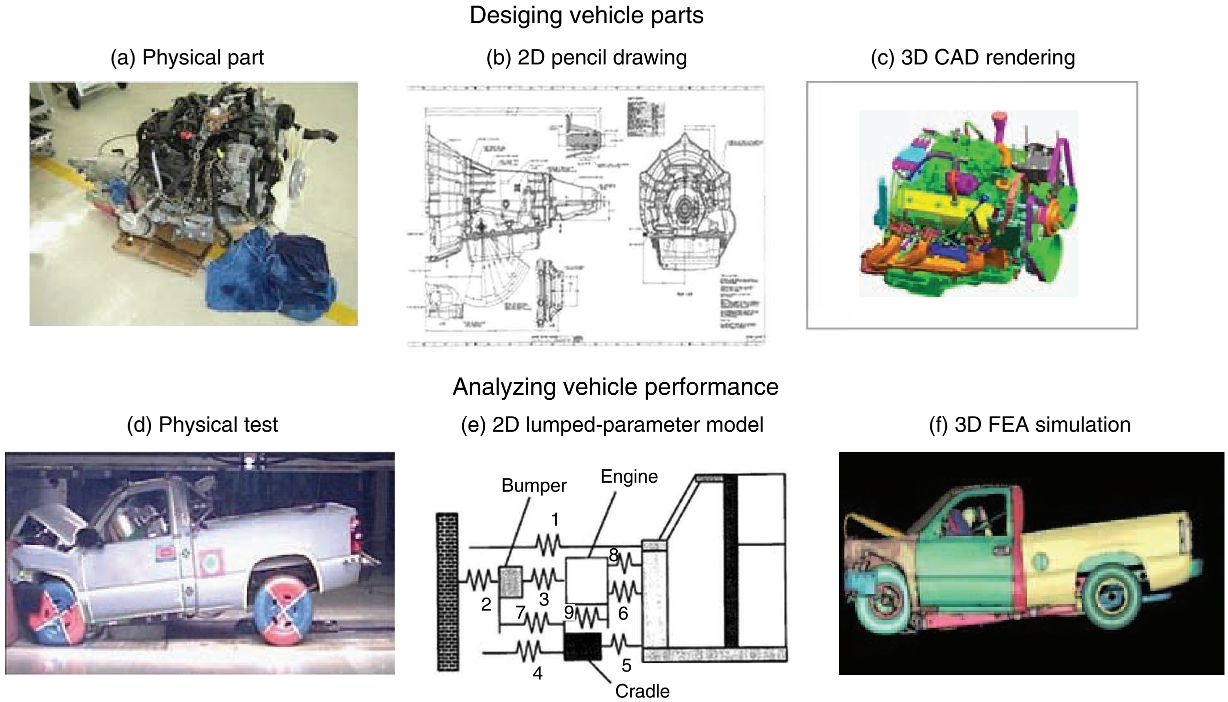
Period 3: Simulating performance				
Role	Design engineer	Test engineer	Simulation engineer	Math tool developer
Task	Design and drawing of parts	Performance analysis (physical)	Performance analysis (math)	Creation of new math tools
Dependence on physical parts	High	High	High (but presumed to be 0 by managers)	Low
Access to physical parts	Moderate	High	Moderate	Low
Task interdependence across roles	High within engineering, moderate across engineering and R&D			
Access to individuals in other roles	Moderate			

Period 4: Offshoring analysis					
Role	Design engineer	Test engineer	Simulation modeler (in India)	Simulation analyst (in the United States)	Math tool developer
Task	Design and drawing of parts	Performance analysis (physical)	Construction of performance models (math)	Analysis of performance models (math)	Creation of new math tools
Dependence on physical parts	High	High	High (but presumed to be 0 by managers and simulation analysts)	High (but presumed to be 0 by managers)	Low
Access to physical parts	Moderate	High	Low	Moderate	Low
Task interdependence across roles	High within engineering, moderate across engineering and R&D				
Access to individuals in other roles	Low				

in the photograph of Figure 1a) or formal engineering drawings (such as the two-dimensional (2D) paper drawing of engine components in Figure 1b). Like all engineering drawings, the drawing of the engine components in Figure 1b is an iconic representation of its referent: the drawing reflects the engine's size and shape as well as the position of its components. At this point, engineers had no technology that could iconically represent how vehicles performed or how parts functioned. Test engineers relied solely on physical tests using real parts and real vehicles, as shown in Figure 1d, a photograph of a frontal impact test.

Whereas the engineers worked with real vehicle parts and on their iconic representations, the R&D group that analyzed vehicle performance worked primarily with symbolic representations of parts and vehicles. In the mid-1960s, the R&D group began using "lumped-parameter" models.[2] An example of such a model is found in Figure 1e. Lumped-parameter models represented vehicles as masses connected by springs. The

Figure 1 Physical Parts/Tests and Their Representations



representations were symbolic, with parts such as the bumper, engine, and cradle in Figure 1e represented by quadrilaterals that in no way mirrored the actual form of the parts. Likewise, one would not find the wiry springs of the lumped-parameter model under the hood of a real vehicle; the springs represented the parts' physical properties and enabled calculations of their performance on impact. Located in a separate building on IAC's main campus, R&D personnel had limited access to physical parts. This was not a problem, however, because R&D did not depend on parts for its work.

R&D modelers used mass-and-spring models' simple mathematical relationships to describe a vehicle's performance. Because lumped-parameter models were symbolic and bore no resemblance to real vehicles, their depiction of a vehicle's performance was not very realistic or accurate. As one simulation engineer who began working in R&D during the late 1960s recalled, symbolic analyses of this type were of little use for engineering work:

> The [lumped-parameter] models were of good theoretical value, but they weren't too practical. They represented some abstract notion of a vehicle, but you couldn't use them to design a vehicle. They were more like a thought experiment to see if we understood what had just happened in a [physical] test and if we could do it in math.... That's why we were in R&D and not engineering.... We worked with ideas of vehicles, but our models didn't really represent vehicles, at least the physical manifestations of them.

That lumped-parameter models were of little use for engineering meant that mathematical analysis of vehicle performance played no role in design. Consequently, task dependence between the engineering groups and the R&D modelers was very low.

Table 4 summarizes the changes in the nature of how vehicle parts, vehicle performance, and people were represented during each of the periods we consider. The table indicates whether the representations used during a period were symbolic, iconic, or indexical. As the rows for Period 1 indicate, 2D paper drawings were iconic representations of the structure of parts, whereas lumped-parameter models were symbolic representations of how vehicles performed. Because lumped-parameter models were so symbolic and at best vaguely referential, engineering had no choice but to rely on physical parts and physical tests to analyze vehicle performance.

Table 4 Changes in the Nature of Representations by Period

		Referent		
Period	Representation	Vehicle part	Vehicle performance	Person
1	2D paper drawing	Iconic		
	Lumped-parameter model		Symbolic	
2	3D CAD rendering	Iconic		
3	3D FEA model	Iconic		
	3D FEA simulation		Iconic	
4	Voice, e-mail, other communication			Indexical

Period 2: Computer-Aided Design Arrives

IAC brought CAD to engineering design in the late 1970s. CAD initially allowed 2D and, eventually, 3D representations of parts and vehicles. CAD renderings, like the paper drawings they replaced, iconically represented the vehicle parts they referenced. As Figure 1c shows, a 3D CAD rendering is a highly detailed and accurate representation of an object's structure (in this case, an engine's).

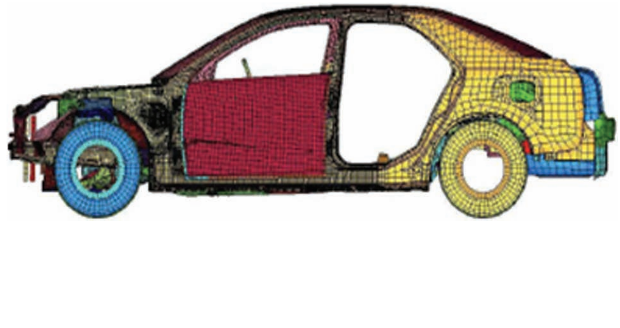
CAD replaced paper with digital drawings, but it did not change engineers' relationship with representations. With CAD, engineers continued to operate on representations. In other words, even though CAD allowed engineers to create and manipulate 3D images, it did not alter the balance of symbolic and iconic representation because paper drawings were already iconic. Consequently, the row for 3D CAD in Table 4 reiterates the row for 2D paper drawings.

CAD renderings did, however, blur the distinction between the work of drafters and parts engineers. As in other settings that adopted CAD, managers realized that with CAD, IAC no longer required the drafters' skills (Cooley 1980, Susman and Chase 1986). Accordingly, they combined the work of drafters and parts engineers into the new role of design engineer. (See the second panel of Table 3.) Despite the shift to CAD, design engineers remained highly dependent on physical parts, as had parts engineers and drafters before them. Similarly, task dependence stayed the same (high among engineering roles, low between engineering and R&D roles). There was simply one less player in the game, and the work of test engineers and R&D modelers was unaffected.

Period 3: Simulating Performance

Although CAD did not significantly alter the balance of iconic and symbolic representation or how engineers worked with representations, the arrival of FEA did. Rather than model an entire vehicle as a handful of masses, as in lumped-parameter models, FEA models require that analysts decompose a vehicle into a large, finite number of small triangular or rectangular areas known as "elements." Adjacent elements are connected at their nodes to define a system of connected elements or a structure called a "mesh." (See Figure 2 for an example of a 3D FEA model with a mesh.) Analysts represent the system of equations that define the mesh as a very large matrix, which they use when simulating vehicle performance.

Figure 2 3D FEA Vehicle Model with Mesh



Early FEA models were nearly as symbolic as the lumped-parameter models they challenged because it was difficult to determine visually whether a simulated vehicle had performed like a real vehicle in a physical test from their 2D output. Therefore, throughout the 1970s, IAC experimented with FEA models in R&D but not engineering. Ultimately, the development of 3D FEA models paved the way for mathematical performance analysis to migrate from R&D to engineering because 3D images made the modeling of performance more iconic and more obviously referential. As one simulation engineer noted,

> When [a 3D application] came out we knew it wouldn't be long before we could move simulation work into the engineering functions. The 3D capabilities let you visualize the vehicle. So the math you did actually gave you a visual representation that corresponded to the actual [physical] vehicle. You could see correspondence between what you were doing and what was happening in the real world.

Nevertheless, as engineers who worked with early versions of FEA observed, the verisimilitude of the representations was still far from adequate:

> I started working with simulation tools in the early '90s.... They were cool because ... you could actually look at your screen and see the vehicle and how it crashed. But they just weren't that accurate. You had a representation of the vehicle, but it didn't have the detail you'd need to really do things. So you could sort of only use it as a supplement to the physical tests. [Simulation engineer]

Getting more accurate results required building more refined FEA models with more and smaller elements. Using a finer mesh, however, required considerable computation. It was not until the mid-1990s, when computers had become sufficiently fast and powerful, that IAC engineers could refine their FEA models. The results of these new models looked increasing like the results of physical tests. Indeed, by the early 2000s, FEA's icons achieved such verisimilitude that they resembled digitized animations of physical crash tests. (Compare Figure 1d with Figure 1f.) The strong resemblance between FEA simulations and physical tests convinced IAC managers that mathematical analysis could ultimately replace physical analysis. They believed that working within representations would become sufficient and that intimate knowledge of the representations' referents would become superfluous:

> We want to move toward doing everything in math so we can have a completely *virtual* [engineering process].... It costs too much to run crash tests and it's too slow to build the vehicles and to staff the testing facilities. Ultimately,

> we want simulations to replace physical testing. We're not there yet, but we're pretty close.... The [simulations] are getting to be so good that our engineers can rely on them and not have to go to the [physical] hardware. [Director of engineering, emphasis added]

As FEA moved into engineering, a new role emerged: the simulation engineer (see Period 3 in Table 3). Simulation engineers spent most of their time in front of a computer screen. They built meshes and models using the CAD files created by the design engineers and analyzed performance digitally. From management's perspective, simulation engineers appeared to work without the need to touch or see physical objects, but in reality, they did not. By moving FEA analysis to engineering, management had provided simulation engineers with de facto access to vehicle parts. Such access was crucial to the simulation engineers' ability to do their work.

For example, one engineer we observed had spent several hours analyzing a simulated crash of a pickup truck. Visually, the FEA model looked identical to the real truck, but the simulated passenger dummy seemed to be hit by an expanding airbag with more force than had the real dummy in the physical test. Frustrated that his model did not match reality, the engineer went to the proving grounds where he sat inside the truck. After inspecting the seat anchors and the seat belt, he turned his attention to the dashboard. This excerpt from our field notes explains his discovery:

> He lifts up the deflated airbag and inspects its connection to the instrument panel. He rubs his finger on a black impression that looks like a smudge of shoe polish. He rotates the bag looking for other signs of the smudge, but sees none other than this one spot. He lets go of the airbag and returns to his exploration of the dash. He runs his hand up the instrument panel and grabs the passenger assist bar located on top of the airbag storage unit. He says, "Hmm," and lifts the plastic flap that once covered the airbag compartment but is still attached, on its top edge, to the dashboard. When lifted, the flap seems to come up about an inch over the top of the bar. He wipes his finger on the inside of the flap and looks at his finger to see that there is a black powdery residue on it. "It looks like there is something going on here," he says out loud.

Returning to his office, the engineer located a video of the physical test. As he watched the crash on his workstation, he noticed that the flap that once concealed the airbag flipped upwards and covered the passenger assist bar as the airbag deployed. He then positioned the simulation in a window next to the video and watched them simultaneously. At that point he noticed that he had not modeled the flap covering the airbag, which meant that the virtual airbag became caught underneath the assist bar, delaying its expansion for 30 milliseconds. In the physical test, the flap flipped up and covered the bar, so the airbag did not get caught underneath. (See the video still in Figure 3a and the simulation still in Figure 3b.) Because the bar temporarily inhibited the virtual airbag's expansion, the virtual dummy had to travel farther to reach the airbag. Consequently, it experienced more force than it would have if the assist bar had not snagged the airbag as it expanded. Had the engineer not noticed the discrepancy between the model and reality while validating his model, the National Highway Transportation and Safety Administration would have given the vehicle a lower occupant protection rating.

The airbag incident reveals that simulation engineers treated FEA models as adequately referential only because they worked tirelessly to validate their mathematical results against the results of physical tests, a process that often demanded that they inspect physical parts. Experienced engineers knew that discrepancies between reality and simulation usually meant that the simulation was flawed. Note, however, that discrepancies could not be discovered and rectified in the absence of the simulation's physical referent. The verisimilitude of the icons that FEA produced could only be assessed relative to the icon's referent, a point that was largely lost on managers.

The simulation engineers' dependence on physical objects spawned a dependence on the engineers who controlled access to those objects. Test engineers controlled access to physical parts and tests that simulation engineers used to validate their models and results. Simulation engineers also depended on design engineers because the latter created and controlled the CAD files from which they built their meshes. In theory, the design engineers also depended on simulation engineers. Managers had shifted FEA analysis to engineering precisely because they wanted design engineers to use the results of the simulations to avoid costly redesign later in the innovation process. Despite management's pressure to treat the simulations as adequate evidence, design engineers often distrusted the models until they saw the same results in physical tests. Regardless, task interdependence among the occupations in engineering remained high (see Table 3).

Because they no longer modeled vehicle performance, R&D modelers began devoting their energies to creating better tools for mathematical analysis. To create new tools, R&D personnel regularly needed access to the design engineers' CAD renderings and the simulation engineers' FEA models for test cases. This need, combined with the fact that R&D now developed tools that engineers would use, reflected increased task interdependence, but not enough to make either functional or physical separation problematic on a day-to-day basis.

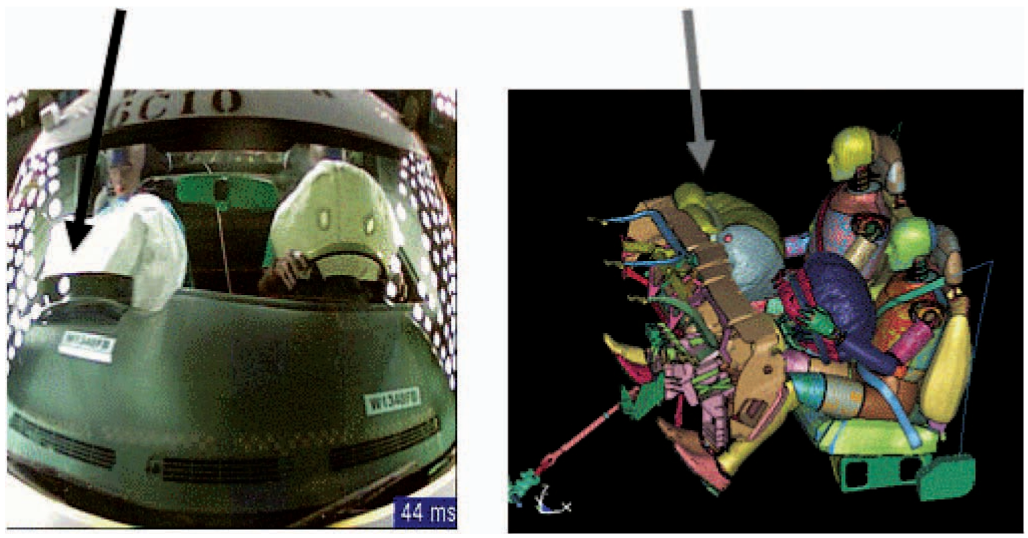
Period 4: Offshoring Analysis

Iconic representations of vehicle performance prompted managers to tout simulation as the way of the future, envisioning a day when the engineering process would be "completely virtual." Managers trusted simulations

Figure 3 Comparison of Airbag Deployment Between Physical Test and 3D FEA Simulation

(a) Physical test: flap blocking bar (normal airbag deployment)

(b) 3D FEA simulation: no flap modeled (airbag caught under bar)



more than the simulation engineers who produced them did. The engineers recognized that it was only reasonable for them to work within representations so long as they could validate the models against the actual parts and processes they were simulating. Consider, for example, the following exchange that occurred during a meeting to chart the design for a particular car program. Participants were looking at simulations projected on a screen:

> Engineer: What we keep getting here [*pausing the animation and pointing with his finger to the location of the engine mounts*] is that the engine mounts break loose.... So then what we did was move the location of the mounts by 12 millimeters.... [*pointing to the new location*] And we get this—let me show you. [*He plays a new animation with the engine mounts in the new position*.] So you can see they stay intact here [*pointing to the location*], which is what we want.
>
> Manager: [*calling on an engineer from another group*] Eric, is that location going to affect the curve in the rail you have, because we want the front end to be low from a design perspective for aero, but also for styling? So will this change that?
>
> Eric: It doesn't look like it. I don't really think so.
>
> Manager: OK, well I say we go with this plan then, if that's the best direction we've got.
>
> Engineer: [*hesitantly*] But we don't know exactly if this is going to work because we have trouble modeling the engine mounts.
>
> Manager: Well, it [the simulation] is showing good performance, right?
>
> Engineer: Yeah, but we're not sure about the weld patterns there, whether they're going to hold. We need to do some [physical] tests of this.
>
> Manager: But the model doesn't show any problems, right?
>
> Engineer: Right.
>
> Manager: Then do we really need the [physical] test?

IAC's growing concerns over engineering costs coincided with the managers' belief that simulation could replace physical tests and prompted senior management to urge engineering managers to favor simulations over expensive physical testing. The engineering managers decided that the way to do more simulations without increasing expensive U.S. headcount was to offshore the work to India, where labor was cheaper:

> When we were thinking about how to scale our simulation work, we realized that we had high fidelity in our models. So, you didn't need to go to the proving grounds each day to map what you were seeing on the screen onto reality. We looked around and said, we've got lots of bandwidth with our Internet backbone. So, it makes sense that we can take things that we could only do in Michigan just a couple years ago and do them anywhere in the world. Maybe even in places where our labor costs weren't quite so steep. It seemed obvious to go to India *because all the information anyone needed to do the work was in the model*. [Senior engineering manager, emphasis added]

The idea that models contained all the necessary information for analysis was equivalent to saying that one could operate within iconic models without recourse to their referents. Managers, therefore, took what they thought was low dependence on the physical as a warrant to offshore simulation to the India center. Importantly,

Table 5 Nine Tasks in Building and Analyzing a Vehicle Performance Simulation Model

1. Build an FEA mesh from CAD files of parts supplied by design engineers.
2. Set the conditions for an FEA model to be run with the mesh.
3. Run a simulation using the model.
4. Analyze and interpret the simulation results.
5. Correlate these results with the physical test to validate the simulation; modify the FEA model if needed and repeat tasks 2–5.
6. Develop improvement ideas for design based on validated simulation results.
7. Create case studies (additional simulations) to test the improvement ideas.
8. Analyze and interpret the results of the case studies.
9. Make recommendations to change the design of parts (and, ultimately, the CAD files).

the India center had no teardown facilities where engineers could inspect parts and no proving grounds where they could observe physical tests. CMC technologies in the form of FTP sites, high-bandwidth Internet connections, and e-mail would allow IAC to rapidly transmit FEA models back and forth between the United States and India. In short, management thought IAC could do simulation analysis effectively using virtual teams, thus combining two types of virtual work.

Although the simulation engineers argued against sending work to India, management insisted. Thus, the engineers divided their work process into the nine sequential tasks, displayed in Table 5. They reasoned that tasks 1–3 (building a mesh and running a simulation model) could be sent to India, but subsequent tasks (analyzing and validating the results, making recommendations) should remain in Michigan. Simulation engineers viewed building a mesh as the least interesting part of their work. They also thought that engineers did not need access to physical referents until they began analyzing and validating a simulation. A simulation engineer explained,

> We do lots of tasks. Most of what we do is analysis, but a lot of our time is just model building. That's routine, sort of standard stuff. It's also not so detailed. What I mean is you're working to build a mesh and you're deciding on how to shape and refine elements and connections. That's all abstract stuff. So, you don't need to look at parts or see tests because real objects don't have elements—they're not divided into boxes for computation. It's just more removed, at that point, from the actual vehicle.

Once offshoring commenced, simulation engineers routinely sent the first three tasks to India, but they almost never sent later steps in the simulation process. The resulting division of labor effectively parsed the simulation engineer's job into two new roles: a simulation modeler residing in India and a simulation analyst residing in the United States (see the bottom panel in Table 3). Task interdependence in engineering remained high (arguably, higher with the splitting of the simulation engineer's role) with no change in engineering's relation to R&D.

As it turned out, the simulation engineers underestimated the importance of the knowledge they gained through regular access to vehicles and parts. As a result, they were wrong in assuming that one could build models without access to their referents. To understand why access was important, we can explore what happened each time a simulation engineer began to build an FEA model from design engineers' CAD files.

Inevitably, whenever a simulation engineer began creating an FEA model from CAD files, some virtual parts jutted through others. Such overlaps occurred because design engineers frequently altered their part's design (and, hence, the CAD files) based on feedback from physical tests and simulations. Changes in the size or shape of one part typically had ramifications for nearby parts. However, because design engineers often neglected to tell each other about changes, the engineers responsible for adjacent parts failed to alter their designs, resulting in an overlap.

Whenever two parts overlapped in the mesh—what engineers called a "penetration"—the simulation engineer would have to decide how to remedy the problem. Because penetrations were numerous, most engineers opted to correct only those for parts that were implicated in the test they intended to run and ignored those that would not meaningfully affect the simulation. Simulation engineers knew which parts of the vehicle were implicated from observing teardowns after physical tests. A simulation engineer explained how he decided which penetrations to correct:

> Well, you just know from seeing the [physical] test. You go see the vehicle after the test and you look and see what areas of the vehicle were impacted—you see what was damaged and what wasn't. You can even touch the parts to get a good sense of it. That gives you a sense of the basic area of the vehicle that will be your load path. That's the area that you have to focus on. All the other areas you can leave because they're not so involved. You just look at test after test after test, and you eventually learn what your model should be like.

Although the Indian engineers were quite technically competent, they immediately encountered problems when fixing penetrations for three reasons. First, because automobiles are not nearly as common in India as they are in the United States, the Indian engineers lacked the American engineers' cultural familiarity with automobiles. Second, because they also lacked access to physical parts and the results of the physical tests that they were asked to simulate, they could not check their models against referents. Finally, the Indian engineers confronted the coordination problems associated with most virtual teams, which, in turn, complicated the other two problems.

Most of the Indian engineers had never driven, much less owned, an automobile. In fact, cars were so rare that most Indian engineers lacked the kind of everyday knowledge of vehicles that Americans take for granted. For example, when asked to develop a model of a fuel system on a truck, an Indian engineer returned a model with a fuel fill pipe and fuel door on both sides of the vehicle. The engineer who developed the model had saved time by using the program's mirror function to reflect the first half of his model to create the second. He did so because he failed to recognize that vehicles have fuel intakes on only one side. The Indian engineers realized that they did not have adequate familiarity with automobiles and that this hampered their ability to fully understand the models they were building and, in particular, to deal with penetrations. To provide experience, managers arranged for the engineers to visit local car dealers, who hoisted vehicles in the air to allow the engineers to examine underbodies. The few Indian engineers who owned vehicles received constant inquiries from their colleagues about various aspects of the vehicle.

Furthermore, because Indian modelers had no access to physical tests or teardowns, they were unsure which penetrations they should fix. Faced with such uncertainty, the modelers sometimes resorted to guessing which parts might be implicated in a particular analysis. Consider the following interaction between Suresh and Vijay, as they examined Suresh's computer screen on which an FEA model for a frontal impact simulation was displayed:

Suresh: There are too many penetrations here [*pointing to an area of the model on the screen*] that need to be cleared up. Richard Danners [the U.S. simulation analyst who requested the work] wants to run a 216 [a specific type of frontal impact test]. Do you think that the parts in the plenum[3] need to be cleared up?

Vijay: I think maybe, but I'm not being so sure. I think for the 208 [another frontal impact test] it is necessary.

Suresh: Maybe these parts are involved only for occupant performance [hence, not the 216 test].

Vijay: I would say to fix that penetration only [*pointing to the penetration in the plenum*], just if you are not sure, then it will be covered.

To compensate for his lack of knowledge of which parts are implicated in the test, Vijay recommended fixing the penetration in the plenum, just in case. In other instances, Indian modelers chose not to fix penetrations. In general, because the choice of which penetrations to fix and which to leave was unguided by examination of parts and physical tests, Indian modelers often left penetrations that would later derail analyses.

On other occasions, Indian engineers chose to fix all of the problems. The approach made the simulation modelers vulnerable to the coordination and communication problems that students of virtual teams repeatedly describe. To build an FEA model, Indian modelers needed the design engineers' CAD files. But whereas the U.S. analysts had access to the CAD repository, the Indian modelers only had access to the files that the U.S. analysts placed on their FTP site. Getting the most recent files required the modelers to ask the simulation analyst to locate and upload the files. Furthermore, determining which part to alter when correcting a penetration required negotiation between the design engineers responsible for the parts. Because Indian modelers had no direct contact with design engineers, they resorted to the guessing described above or routed their queries through the simulation analyst. In this manner, the discrepancy between the dependence on and access to objects was amplified by mismatched task interdependence created in part by the shift to virtual teams.

As Table 3 indicates, the distribution of work in Period 4 created mismatches between the Indian engineer's high dependence on, but low access to, parts. Moreover, the organization of work into virtual teams meant that the Indian engineers lacked easy access to engineers on whom they depended for crucial information. Such large discrepancies had never appeared before: in Periods 1–3, when access was low, so was dependence. The large discrepancies faced by the Indian modelers created significant problems in simulation work.

Discussion

By turning to semiotics to analyze the representations made possible by digitization, and by tracing how new representations prompted increased virtuality in work, our study demonstrates how simulation can engender changes in the work structure as well as in tasks and roles. It also speaks to how problems encountered in simulation, particularly with respect to trust, may differ from what has been documented in studies of the other two types of virtual work—namely, virtual teams and remote control. In so doing, our study helps to specify how the organization of work might change under simulation (it begins to fill in, as it were, the empty boxes in Table 2). More broadly, our study provides the underpinnings for building theories of virtual work through a focus on representations. In addition, and more practically, our study highlights the dangers inherent when managers confuse one type of virtual work with another.

Work Structure

On virtual teams, digitization permits separation between people who use indexical representations of one another to carry out mediated communication. In remote control, digitization enables separation between people and objects; operators use symbolic and iconic representations of objects and physical processes to monitor, manipulate, and alter the objects and processes from a distance. Working across distances (for the purposes of collaboration in the first case and control in the second) is a key element of work structure in both cases.

Simulation differs from virtual teams and remote control in this respect. Although digitization allows for separation between people and objects or other people, the purpose of virtuality has nothing to do with distance. The purpose of virtuality in the case of simulation is study and experimentation. The very names of the three types of virtual work make clear this distinction. The word "team" is preceded by "virtual," the word "control" is preceded by "remote," but the word "simulation" lacks a modifier: we do not speak of virtual simulation or remote simulation. In short, with virtual teams and remote control, the entire point of organizing work virtually is to take advantage of digitization's affordance of spatial separation. The point of simulation is not to take advantage of spatial separation but to take advantage of the independence between people and objects or other people, if only for short periods of time.

That the period of time is short speaks to the fact that this independence is bounded. Ultimately, the creators of simulations must return to the objects or people that they aim to represent to test and validate their models. Each subsequent change in the model requires yet more validation. Thus, with simulation, physical objects or other people become deceptively distant but remain absolutely vital, not because workers' manipulations are intended to directly affect these entities, but because the entities are the referents of representations. Simulations with high verisimilitude appear to substitute for objects or other people because one can do within representations what one could previously do only with physical entities themselves. The adequacy of such simulations, however, still depends on validating their results against physical objects, people, and their associated processes.

Other organizational studies of digital technologies have noted the tight coupling between representations and referents. In the Dodgson et al. (2007) study of simulation in fire engineering, engineers used fire drills to validate their models. Real fires were another source for comparison and validation. One fire engineer remarked, "We always try to iterate between real cases of fire and our models"; another commented, "We are continuously interrogating our models . . . evidence from a fire can challenge our ideas" (Dodgson et al. 2007, p. 856). Similarly, Yoo et al. (2006) observed that Frank Gehry's architectural firm maintained a tight coupling across 3D digital representations, 2D paper drawings and sketches, physical models, and actual buildings. The architectural team continually translated and validated Gehry's design vision across these disparate media over the course of a design process. Such tight coupling between representations and referents provides clear implications for the structure of simulation work.

As our study of automotive engineers shows, this tight coupling in simulation means that the people who create representations are highly dependent on physical referents. Consequently, the creators of representations need a work structure that provides good access to the objects or people represented. In the case of objects, the creators also need ready access to the people who control the objects, a fact that illustrates how dependence on objects can breed task interdependence. Thus, in the case of simulation, although digitization permits separation of people from the referents of representations, virtuality may still demand proximity. Managers, therefore, should structure simulation work such that people have ready access to the physical entities and processes they model.

Tasks and Roles

Researchers rarely report that virtual teams alter either work roles or the division of labor. Most likely, researchers are silent on the matter because such teams are often formed to take advantage of distant experts who play their existing work roles in the same skilled manner regardless of where their teammates are located (Boh et al. 2007, Sole and Edmondson 2002). By contrast, researchers often report that remote control threatens significant change in the division of labor. In paper mills, for example, digital controls place considerable information in the hands of operators, potentially enabling them to make operational decisions traditionally reserved for managers. Although some mills have embraced such fundamental changes in the division of labor, most have not, because managers are hesitant to cede authority to operators and operators are hesitant to shoulder the responsibility of making decisions (Zuboff 1988).

Like remote control, simulation appears to spawn changes in the division of labor. At IAC, these changes were closely associated with the deployment of increasingly sophisticated, iconic simulations. When FEA models replaced lumped-parameter models in Period 3, mathematical performance analysis shifted from R&D to engineering, thereby creating the new role of a simulation engineer. Unlike R&D modelers, whose models were symbolic, not iconic, simulation engineers required access to vehicle parts and were highly dependent on other engineering occupations for accomplishing their work. The move to engineering signified the rise in the importance of the modeling role within product development; managers now expected modelers to inform design decisions.

The story, however, does not end there. When managers became convinced that iconic representations of performance were so accurate that simulation engineers did not need access to physical referents, they altered the division of labor once again. By offshoring model building to India, managers split the simulation engineer's role into two new occupations: simulation modelers (in India) and simulation analysts (in the United

States). This change in tasks and roles reflects an attempt at work rationalization that was absent in earlier changes at IAC: engineers in the United States sent the less interesting and routine tasks to the Indian modelers, keeping highly analytic tasks for themselves. They also thought the tasks they sent to India were ones that could be divorced from physical referents. This presumption turned out to be untrue, as problems in the models quickly attested.

These changes in tasks and roles at IAC resonate with arguments that digital modeling technologies are apt to bring profound changes to work roles within and across organizations. The advent of technologies that permit the simulation of fire, smoke, and human evacuation of buildings prompted the creation of a new engineering profession: fire engineering (Dodgson et al. 2007). As new actors working amidst insurers, regulators, architects, building authorities, and engineers of various hues (structural, mechanical, electrical, environmental, and so on), fire engineers carved out a role for themselves in the design process for safe buildings. Boland et al. (2007) noted how architect Frank Gehry's adoption of digital 3D technologies disrupted established practices among architects, engineers, and contractors on his projects, allowing them to forge new relationships among actors, and, in so doing, to innovate considerably. A European automaker defied its traditional functional organization to create a new team consisting of several designers, a simulation engineer, and a physical test engineer. By using the rapid feedback that simulation provided, the team could quickly iterate through design solutions, ultimately improving crash safety by 30% at a fraction of the cost of the traditional development process (Thomke 2003). Subsequently, the automaker began dramatic changes in work processes and organization to extend the benefits that this small team demonstrated. These examples demonstrate the kinds of sweeping changes in tasks and roles that are likely to emerge as the use of simulation spreads across occupations and industries. Our study further points to potential pitfalls that may arise if these changes fail to take into account each role's relationship to representations.

Related Problems of Trust

One common theme in Table 2's list of problems associated with each type of virtual work is trust. Students of virtual teams report that members have difficulty trusting distant coworkers, a situation that is troublesome because a lack of trust undermines team performance (Iacono and Weisband 1997, Jarvenpaa and Leidner 1999). Issues related to trusting others also arise in remote control, but here, they are primarily between managers and workers. In this sense, remote control reopens the rift between conception and execution that has long underwritten issues of power, authority, and trust in industrial settings (Noble 1984, Shaiken 1984, Vallas and Beck 1996).

More interestingly, studies of remote control foreground an entirely different type of trust and distrust: the advisability of trusting representations. In paper mills, operators were overly suspicious of the representations' accuracy because they were accustomed to gathering information by seeing, hearing, touching, and smelling equipment and paper (Zuboff 1988). In fact, some operators distrusted the symbols on their monitors so much that they insisted on walking by the mill's vats and presses to make sure, as one worker explained, that "the machine [control system] ain't lyin' to you" (Vallas and Beck 1996, p. 347). As Perrow (1999) and Hirschhorn (1984) noted in their discussion of remote control in nuclear power plants, potentially even more serious problems occur when operators trust representations too much.

Placing too much trust in representations was precisely the problem that accompanied the development of FEA simulations at IAC. Lured by the robustness of FEA's iconic representations, managers made decisions based on their trust in simulation models, even when engineers desired physical tests as confirmation. This trust is what prompted managers to order the offshoring of model building to India against the advice of the American engineers, who understood the importance of validating simulations against their referents.

Such findings resonate with studies showing that users of models are often less skeptical of their results than are the models' creators (Shackley and Wynne 1996, MacKenzie 1990). For example, Boland et al. (2007) noted that construction managers encouraged window contractors to forgo taking field measurements of openings in concrete walls and to rely instead on simulation data to determine window size. Similarly, managers in the crash division at the European automaker encouraged engineers to use data from simulation models as opposed to physical test data to redesign the front section of a sport utility vehicle (Thomke 2003).

The Indian engineers similarly placed too much faith in their model's results. In the absence of knowledge gained from direct contact with physical objects and processes, the Indian engineers acted in a manner consistent with Turkle's (2009) engineering students: they treated their representations as if they were "real." In short, like managers and engineering students, the Indian engineers succumbed to the lure of the virtual.

Building Theory, Beginning with Representations

Table 1 constitutes a taxonomy of virtual work in organization studies. Taxonomies are useful for illuminating descriptive differences and for identifying meaningful constructs. For example, the taxonomy in Table 1 helped us conceptually differentiate digitization from virtuality. Digitization affords spatial separation, which virtuality may or may not be wise to exploit. Digitization gives rise to the divide between the physical and virtual through the creation of digital representations; virtuality specifies what the interaction between the physical and virtual will be. Representations forge the link between digitization and virtuality. Students of digitization and work ignore virtuality and representations at their peril because it is the combination of digitization, virtuality, and representations that permits distinctions among types of virtual work.

Generally speaking, the type of representations that virtual workers use varies by the type of virtual work. Virtual teams often use indexical representations of members; they are also likely to use symbolic representations that lack physical referents (e.g., budgets, reports). In remote control, symbolic and low verisimilitude iconic representations populate the digital interfaces of computer control systems. High verisimilitude iconic representations typify simulation. Associated with differences in types of representation are differences in workers' relationship to the representations. Members of virtual teams primarily operate *with or on* representations, people in remote control operate *through* representations, and creators of simulations operate *within* representations. As our study demonstrates in the case of simulation, these differences in types of representations and relationships to representations are central to explaining dependencies on objects and people at work. As such, they also set the parameters for access to objects and people. Beyond having implications for the design of work, as we have discussed, differences in the nature of representations point the way for building theories of virtual work.

For example, our case study suggests that, in simulation, the fit between dependence on the referents of representations and access to those referents is predictive of performance. That is to say, when simulation at IAC was wholly situated in the United States, simulation engineers' dependence on vehicle parts and other people was paired with ready access to those parts and people. When IAC offshored simulation to India, however, simulation engineers' high dependence on vehicle parts and other people was suddenly paired with low access to those parts and people. Problems in the quality of simulation models quickly arose, underscoring the criticality of access for performance when dependence is high. These problems may not be universal to virtual work. They cannot arise, for example, when individuals work on representations that have no referent, and for this reason, they may be less prevalent among virtual teams than in simulation.

Most discussions of dependence in organization studies focus on dependence among people, or what is called task interdependence (Wageman 1995, Thompson 1967).[4] Workers' dependence on physical objects rarely attracts scholars' attention because the objects are always proximate to the workers, making access simple. When objects are digitized and then made virtual, ready access to them may no longer be available to workers. At that point, scholars can no longer take physical objects for granted; rather, objects must jump to the forefront of our analyses. In short, when considering virtual work, organizational theorists and work systems designers alike ought to pay attention to representations as a first step, and then to workers' dependence on and access to the physical referents of representations as a second.

Confusing One Type of Virtual Work for Another

We conclude by noting that the developments at IAC illustrate that the changes in work associated with virtual work become more complicated when managers confuse one type of virtual work for another. IAC's managers failed to appreciate how operating *within* representations differed from operating *with or on* representations. They correctly understood that having access to physical objects was relatively unimportant for tasks that involved operating on representations that have no referents. They also understood that such work could be done by virtual teams, although it might be subject to communication and coordination problems that arise when people attempt to operate with indexical representations of team members. What they failed to grasp was how important it was for model builders to have access to the physical objects and processes they were simulating. Consequently, they confused operating within representations with operating with or on representations. In fact, they chose Bangalore as the site for the India technical center precisely because it was known as an offshoring hub, the perfect location for finding people experienced in working *with or on* representations. Had they recognized that building adequate simulations requires validation against physical referents, they may not have sent the work to India.

IAC's managers eventually realized that their dream of a completely virtual automotive design process still lay in the realm of science fiction. When it became clear that problems with offshored FEA models were not declining, they recognized that simulation engineers needed access to the physical referents of iconic representations. Accordingly, IAC installed a teardown room in the India center where engineers could handle and inspect vehicle parts. The firm also joined other automotive companies in India to build a proving ground for physical testing. Thus, IAC used a strategy similar to that which scholars advise firms to use to mitigate the problems of virtual teams: they removed the distance associated with virtuality (Maznevski and Chudoba 2000, Hinds and Bailey 2003). In the case of virtual teams, eliminating distance is typically temporary and involves face-to-face meetings or sending distant members to visit the team's primary location.[5] In the case of simulation, eliminating distance between simulators and objects is a permanent proposition.

Ours has been a cautionary tale about the lure of the virtual. Organizations usually turn to the virtual in all of its forms in the hopes of reducing costs by replacing humans and objects with representations or by employing less expensive labor. The lure of the virtual appears difficult for firms to resist. For example, despite considerable evidence that virtual teams are less effective and more troublesome than colocated teams, organizations continue to employ them. Thus, when managers choose to make objects, rather than people, virtual, it is perhaps fortunate that they will encounter problems that they cannot skirt by instructing people to exert more effort or to simply make do. Faulty remote control systems and simulations can have catastrophic consequences, such as plant disasters and product recalls. When faced with problems of such magnitude, organizations must learn to resist the lure of virtual work. Our admonition is that they should learn to do so with foresight rather than hindsight.

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Endnotes

[1]In the setting we studied, no one used remote control; hence no one operated through representations. Although remote control technology can be found in some of IAC's settings, particularly manufacturing, we did not encounter it in the groups we studied.

[2]A lumped-parameter model is so named because it describes the relationships among system components without explaining the particular functioning of each parameter. Instead, the parameters are "lumped together" to render an acceptable output.

[3]A plenum is a ventilation duct designed to allow air circulation for heating and air conditioning systems. By definition, no parts should penetrate the plenum to avoid obstructing air flow.

[4]For an exception, see the Bailey et al. (2010) study of dependence among work technologies.

[5]Some evidence suggests that even this mitigation strategy is insufficient in the case of virtual teams. Metiu (2006) reported that when distant Indian members of a software development team temporarily relocated to California to be with the rest of the team, they still remained socially isolated from, and had limited interaction with, their U.S. counterparts.

References

Bailey, D. E., P. M. Leonardi, J. Chong. 2010. Minding the gaps: Understanding technology interdependence and coordination in knowledge work. *Organ. Sci.* **21**(3) 713–730.

Barley, S. R. 1996. Technicians in the workplace: Ethnographic evidence for bringing work into organization studies. *Admin. Sci. Quart.* **41**(3) 404–441.

Black, M. 1962. *Models and Metaphors: Studies in Language and Philosophy*. Cornell University Press, Ithaca, NY.

Boh, W. F., Y. Ren, S. Kiesler, R. Bussjaeger. 2007. Expertise and collaboration in the geographically dispersed organization. *Organ. Sci.* **18**(4) 595–612.

Boland, R. J., Jr., K. Lyytinen, Y. Yoo. 2007. Wakes of innovation in project networks: The case of digital 3-D representations in architecture, engineering, and construction. *Organ. Sci.* **18**(4) 631–647.

Chaminade, C., J. Vang. 2008. Globalisation of knowledge production and regional innovation policy: Supporting specialized hubs in the Bangalore software industry. *Res. Policy* **37**(10) 1684–1696.

Cooley, M. 1980. *Architect or Bee? The Human/Technology Relationship*. South End Press, Boston.

Cramton, C. D. 2001. The mutual knowledge problem and its consequences for dispersed collaboration. *Organ. Sci.* **12**(3) 346–371.

Csordas, T. J. 2001. Computerized cadavers: Shades of representation and being in virtual reality. P. P. Brodwin, ed. *Biotechnology and Culture: Bodies, Anxieties, Ethics.* Indiana University Press, Bloomington, 173–192.

Cunningham, J. 2007. Simulation makes big savings. *Professional Engrg.* **20**(21) 39–40.

Dodgson, M., D. M. Gann, A. Salter. 2007. "In case of fire, please use the elevator": Simulation technology and organization in fire engineering. *Organ. Sci.* **18**(5) 849–864.

Drew, C. 2009. Drones are weapons of choice in fighting Qaeda. *New York Times* (March 17) A1.

Eco, U. 1979. *A Theory of Semiotics*. University of Indiana Press, Bloomington.

Faraj, S., L. Sproull. 2000. Coordinating expertise in software development teams. *Management Sci.* **46**(12) 1554–1568.

Frege, G. 1892/1980. On sense and reference. P. Geach, M. Black, eds. *Translations from the Philosophical Writings of Gottlob Frege*. Blackwell, Oxford, UK, 25–50.

Gibson, C. B., J. L. Gibbs. 2006. Unpacking the concept of virtuality: The effects of geographic dispersion, electronic dependence, dynamic structure, and national diversity on team innovation. *Admin. Sci. Quart.* **51**(3) 451–495.

Griffith, T. L., J. E. Sawyer, M. A. Neale. 2003. Virtualness and knowledge in teams: Managing the love triangle of organizations, individuals, and information technology. *MIS Quart.* **27**(2) 265–287.

Handy, C. 1995. Trust and the virtual organization. *Harvard Bus. Rev.* **73**(3) 40–50.

Hinds, P. J., D. E. Bailey. 2003. Out of sight, out of sync: Understanding conflict in distributed teams. *Organ. Sci.* **14**(6) 615–632.

Hirschhorn, L. 1984. *Beyond Mechanization*. MIT Press, Cambridge, MA.

Iacono, S., S. Weisband. 1997. Developing trust in virtual teams. *Proc. 30th Annual Hawaii Internat. Conf. System Sci.*, IEEE Computer Society Press, Los Alamitos, CA, 412–420.

Jarvenpaa, S. L., D. E. Leidner. 1999. Communication and trust in global virtual teams. *Organ. Sci.* **10**(6) 791–815.

Kanawattanachai, P., Y. Yoo. 2002. Dynamic nature of trust in virtual teams. *J. Strategic Inform. Systems* **11**(3–4) 187–213.

Kincaid, J. P., J. Donovan, B. Pettitt. 2003. Simulation techniques for training emergency response. *Internat. J. Emergency Management* **1**(3) 238–246.

Kurowski, P. M. 2008. Expecting too much from FEA. *Machine Design* (July 10) 89–93.

Levina, N., E. Vaast. 2008. Innovating or doing as told? Status differences and overlapping boundaries in offshore collaboration. *MIS Quart.* **32**(2) 307–332.

Longridge, T., J. Bürki-Cohen, T. H. Go, A. J. Kendra. 2001. Simulator fidelity considerations for training and evaluation of today's airline pilots. *Proc. 11th Internat. Sympos. Aviation Psych., Ohio State University, Columbus*.

Macedonia, M. 2002. Games soldiers play. *IEEE Spectrum* **39**(3) 32–37.

MacKenzie, D. 1990. *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance.* MIT Press, Cambridge, MA.

Marescaux, J., F. Rubino. 2004. Robot-assisted remote surgery: Technological advances, potential complications, and solutions. *Surgery Tech. Internat.* **12** 23–26.

Maznevski, M. L., K. M. Chudoba. 2000. Bridging space over time: Global virtual team dynamics and effectiveness. *Organ. Sci.* **11**(5) 473–492.

Metiu, A. 2006. Owning the code: Status closure in distributed groups. *Organ. Sci.* **17**(4) 418–435.

Miles, M. B. 1979. Qualitative data as an attractive nuisance: The problem of analysis. *Admin. Sci. Quart.* **24**(4) 590–601.

Miles, M. B., A. M. Huberman. 1994. *Qualitative Data Analysis: An Expanded Sourcebook*, 2nd ed. Sage, Beverly Hills, CA.

Noble, D. E. 1984. *Forces of Production: A Social History of Industrial Automation*. Oxford University Press, Oxford, UK.

Peirce, C. S. 1932. *Elements of Logic: Collected Papers of Charles Sanders Peirce*, Vol. 2. Edited by C. Hartshorne, P. Weiss. Harvard University Press, Cambridge, MA.

Perrow, C. 1983. The organizational context of human factors engineering. *Admin. Sci. Quart.* **28**(4) 521–541.

Perrow, C. 1999. *Normal Accidents: Living with High-Risk Technologies*, revised ed. Princeton University Press, Princeton, NJ.

Prentice, R. 2005. The anatomy of a surgical simulation: The mutual articulation of bodies in and through the machine. *Soc. Stud. Sci.* **35**(6) 837–866.

Quine, W. V. O. 1961. *From a Logical Point of View: Nine Logico-Philosophical Essays.* MIT Press, Cambridge, MA.

Satava, R. M. 1995. Virtual reality and telepresence for military medicine. *Comput. Biol. Medicine* **25**(2) 229–236.

Saussure, F. d. 1916/1966. *Course in General Linguistics*. Edited by C. Bally, A. Sechehaye. Translated by R. Harris. McGraw-Hill, New York.

Shackley, S., B. Wynne. 1996. Representing uncertainty in global climate change science and policy: Boundary-ordering devices and authority. *Sci. Tech. Human Values* **21**(3) 275–302.

Shaiken, H. 1984. *Work Transformed: Automation and Labor in the Computer Age*. Holt, Rinehart, and Winston, New York.

Sole, D., A. Edmondson. 2002. Situated knowledge and learning in dispersed teams. *British J. Management* **13**(S2) S17–S34.

Sproull, L., S. Kiesler. 1991. *Connections: New Ways of Working in the Networked Organization*. MIT Press, Cambridge, MA.

Susman, G. I., R. B. Chase. 1986. A sociotechnical analysis of the integrated factory. *J. Appl. Behav. Sci.* **22**(3) 257–270.

Thomke, S. H. 2003. *Experimentation Matters: Unlocking the Potential of New Technologies for Innovation*. Harvard Business School Press, Boston.

Thompson, J. D. 1967. *Organizations in Action: Social Science Bases of Administrative Theory*. McGraw-Hill, New York.

Thornton, J. 2010. The question of credibility. *Mech. Engrg.* **132**(5) 40–45.

Tschang, F. T. 2007. Balancing the tensions between rationalization and creativity in the video games industry. *Organ. Sci.* **18**(6) 989–1005.

Turkle, S. 2009. *Simulation and Its Discontents*. MIT Press, Cambridge, MA.

Vallas, S. P., J. P. Beck. 1996. The transformation of work revisited: The limits of flexibility in American manufacturing. *Soc. Problems* **43**(3) 339–361.

Wageman, R. 1995. Interdependence and group effectiveness. *Admin. Sci. Quart.* **40**(1) 145–180.

Yin, R. K. 1994. *Case Study Research: Design and Methods*, 2nd ed. Sage, Beverly Hills, CA.

Yoo, Y., R. J. Boland Jr., K. Lyytinen. 2006. From organization design to organization designing. *Organ. Sci.* **17**(2) 215–229.

Zuboff, S. 1988. *In the Age of the Smart Machine: The Future of Work and Power*. Basic Books, New York.

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