Networks of Innovation:
The Sociotechnical Assemblage of Tabletop Computing

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Abstract

We theorize on the heterogonous network of people, visions, concepts, technological artifacts, and organizations that come together to enable product innovation. Drawing on the conceptual framing and mechanisms of actor-network theory (ANT), we focus on the relationships among human and non-human actors and their roles to enact new products. We do this to contribute both evidence and theory regarding the concept of a sociotechnical assemblage that serves as the innovation network. Advancing a sociotechnical conceptualization of innovation focuses attention on the contributions of, and linkages among, different types of actors; individuals and organizations, visions and concepts, and technological artifacts and prototypes together create a means for innovation to occur. The empirical basis for this theorizing comes from a detailed study of the community of research scientists, faculty, and graduate students; institutions such as research labs, funding sources, and product companies who were (and mostly still are) involved in tabletop computing. Analysis highlights the centrality of visions, concepts and technological artifacts in the innovation network. We also find that formal organizations play important, but often unrealized, roles in supporting innovation.

Keywords:

Innovation network, actor-network theory, sociotechnical assemblage, tabletop computing,

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1. Introduction

We theorize on the networks of people, visions, concepts, technological artifacts and organizations that come together to enable product innovation. Drawing on the conceptual framing and mechanisms of actor-network theory (ANT), we focus on the ways in which the set of relationships among human and non-human actors ("actants" in ANT's terminology) serve as both the frame for and the mechanism to enact a new product. We do this to contribute both evidence and theory to articulate the concept of a sociotechnical "innovation network" (e.g., Brennecke and Rank 2017; Lawlor and Kavanagh 2015). Some readers might consider our use of ANT as a contribution, though our attention is toward the sociotechnical conceptualization of innovation. For the work reported here, ANT serves as the conceptual vehicle and not the focus or goal of our theorizing.

Advancing a sociotechnical conceptualization of innovation focuses attention on the contributions of, and linkages among, different types of actors such as individuals and organizations, and to the roles of visions, concepts, and technological artifacts. Together, these human and non-human elements of a network create a means for innovation to occur. The empirical basis for this theorizing comes from a detailed study of a community of research scientists, faculty, and graduate students, institutions such as research labs, funding sources, and product companies who were (and mostly still are) involved in the nascent area of tabletop computing (with Microsoft's PixelSense[2] as the most well-known product). Combining iterations of bibliometric analysis, interviews, and data drawn from secondary sources, we identified core elements of the innovation network across the 17 years prior to PixelSense's 2012 market introduction. Doing so helped us to draw out the ways in which products emerge from the relationships and interactions among people, visions, concepts, technologies, and institutions.

To help advance these contributions, the paper is developed in seven more sections. In the next section (section two), we provide an overview of tabletop computing to frame the empirical basis of the work. In section three, we summarize current work on informal networks of innovation and highlight the under-theorized roles of artifacts. In section four, we review the core concepts of the actor-network perspective relative to its use here. We outline the data collection and analysis in section five. In section six, we present the actor-network of tabletop computing; and, in section seven, we use insights from the analysis to frame our discussion on the sociotechnical structure of innovations. Finally, in section eight, we advance two areas for research on innovation arising from this work.

2. The Empirical Basis: Tabletop Computing

The empirical basis for this work is a detailed micro-study of research scientists, faculty members, graduate students, and others involved in basic research, applied research, and product development in the area of *interactive surface* or *tabletop computing* (henceforth called tabletop computing). Tabletop interfaces embody collaborative use via a tangible interface that provides for gesture recognition and interactive visualizations. These (typically) horizontal interfaces (in contrast to the vertical screens most of us are familiar with on our computers) support small group interaction by allowing multiple people to

[2] For more on this product, see https://www.windowscentral.com/microsoft-surface-pixelsense-table.

directly interact with digital information at the same time, without using keyboards and mice (Müller-Tomfelde and Fjeld 2010).

To date, the most well-known commercial tabletop product to come from this community is Microsoft's PixelSense.[3] PixelSense is aimed for the hospitality and entertainment industries (e.g., large hotels, casinos, and restaurants). SMART Technologies has introduced their Table 230i [4] targeted to the education sector. Other tabletop products include Ideum's multi-touch table [5] and Samsung SUR40.[6]

Developing a tabletop computing product requires a wide range of technical expertise and draws together computer scientists involved in multi-touch displays, gesture recognition, and multi-image processing with scholars of human–computer interaction (HCI), visualization, and computer-supported collaborative work (CSCW). Tabletop scholars are centered in a finite number of institutions (and these institutional homes change over time as people move around). Manufacturing is centered on a few large technology companies and several start-ups, all with strong connections to relevant academic research. This noted, we focus on the development phase of innovation, so our analysis does not include innovations and events that occurred after the initial products were brought to market in 2012 (e.g., technology adoption and domestication).

We selected the tabletop computing community for conceptual and pragmatic reasons. Conceptually, it is a sterling example of a research community connected to product development, allowing us to develop insights into innovation. By many measures, the community can be seen as intellectually prolific because of the high rate of innovation in their work. Pragmatically, as we began our research, tabletop computing's first commercial products were just entering the market, making a study of the form we pursued timely. Finally, the community is relatively well bounded, making it just a bit easier to study. Here, we focus on the larger network of individuals, institutions, ideas, and artifacts that served as the innovation ecosystem for each of the companies building tabletop computing products.

3. Research on Informal Networks of Innovation

Like others, we conceive of the innovation process as both complex and multipronged, encompassing the generation of novel ideas for products and services through to the creation of business processes or products and technological capabilities (Bartel and Garud 2009; Van de Ven et al. 1999). Like others, we see innovation as critical to economic success: this is why "innovation studies" (Fagerberg et al. 2012) draw considerable scholarly attention from multiple intellectual communities such as economics, organizational studies, information systems, science and technology studies (STS), and others (e.g., Callon 2002; Gay and Dousset 2005; Nelson and Winter 1982; Owen-Smith and Powell 2004; Perez 2010).

3.1. The Roles of Networks in Innovation

Empirical work on innovation makes clear that the outcomes arise from contributions of multiple players' participation (Brown and Duguid 2001; Lyytinen et al. 2016; Prince et al. 2014), and that the

[3] http://www.pixelsense.com
[4] https://smarttech.com/Support/Browse+Support/Product+Index/Hardware+Products/SMART+Table/230i
[5] http://ideum.com/touch-tables/platform
[6] http://samsung.com/Business-LFD

knowledge needed to innovate is located with players—many of whom are part of different institutions (Lawlor and Kavanagh 2015; Mezias and Kuperman 2001). Scholars consider networks of relevant actors to be the fundamental organizing structure of innovation, acknowledging in doing so that new technologies and products are seldom developed by a single firm (Möller and Svahn 2009; Naghizadeh et al. 2017). Necessary skills and know-how needed for innovation typically are spread across multiple firms (Powell 2000; Schilling and Phelps 2007). Teece and Pisano (1987) noted, more than 30 years ago, that large corporations are acutely aware that innovation knowledge is often situated outside their boundaries. Contemporary organizations are aware they are even less self-sufficient in their ability to generate knowledge to drive innovation processes (Fusfeld and Haklisch 1985; Powell and Grodal 2005; Ujjual and Patel 2013).

Scholars have noted that focusing on firms as the locus of innovation and formal ties established among them masks the dynamic and informal nature of social relationships that undergird innovation processes (Cockayne 2004; Cross 2011; Van Aken and Weggeman 2000). As Powel et al. (1996, p. 120) note: "Beneath most formal ties lies a sea of informal ties." Informal relationships are reified in the form of interest groups which span multiple organizations, and may not necessarily be recognized by the formal organizations that employ their members (Krackhardt and Hanson 1993; Salavisa et al. 2012).

Studies of formal inter-firm networks (taking firms and their relations as the primary unit of analysis) provide a useful but incomplete picture of innovation (Powell and Grodal 2005). Focusing attention to informal networks provides insight into the less visible, but important, structures of social organizing (Contractor et al. 2006; Fu et al. 2013). Informal ties are salient because they enhance knowledge exchange and the generation of new, valuable information, even if they evolve into formal arrangements (Cross et al. 2003; Jarrahi and Sawyer 2013).

Indeed, much of the relevant organizational research on social networks has been concerned with complex webs of communication among individual actors that can afford access to intangible assets such as tacit knowledge and technological innovation, something which cannot be as readily developed internally by any one organization (e.g., Capaldo 2007; Gay and Dousset 2005; Obstfeld 2005; Powell et al. 1996; Rothaermel and Hess 2007). For example, Uzzi and Spiro (2005) illustrate that small world arrangements inspire innovation as they connect the specialized knowledge and resources embedded within multiple clusters that would be isolated otherwise. This focus is understandable given the commonly held assumptions about the primary players in innovation networks and scholars often use the concept of "networks of innovators" to make this point (e.g., Cantner and Graf 2006; DeBresson and Amesse 1991; Freeman 1991; Graf 2011; Powell and Grodal 2005).

The literatures of both organizational studies and science studies provide relevant insights into the constituents and structures of informal networks relative to innovation. For instance, useful insights can be found in theoretical work related to the informational and status-providing advantages of having social ties with others (e.g. Burt 1992; Granovetter 1982; Krackhardt 1990; Merton 1957; Wellman 1979). Their work suggests that networks of relations are enacted through sharing information among nodes (people) via ties (the means of interacting with the nodes). Social networks typically span the boundaries of any formally-defined organization (Cross and Parker 2004; Prince et al. 2014). This boundary crossing is done by boundary spanners or brokers (formally or informally), who can serve as bridges across boundaries (Klerkx and Aarts 2013; Lee 2010; Liebeskind et al. 1996; Obstfeld 2005).

Specifically relevant to innovation, science studies scholars have built on concepts of social networks and have embraced the concept of an invisible college, specifically denoting a group of researchers or scientists who work together closely or share similar scholarly interests, even though they work for different institutions (or units within a larger enterprise) (Fagerberg and Verspagen 2009; Sedita et al. 2018; Zuccala 2006). An invisible college is a set of relationships among scholars that spans both institutional boundaries and geographical space (Quan-Haase et al. 2015; Verspagen and Werker 2003). These collaborations often extend beyond national scales to incorporate "all other countries in which that specialty is strong" (Price 1986, page 119). In principle, belonging to and participating in these informal networks of scholars helps their members advance their careers and interests (Gherardini and Nucciotti 2017). An invisible college is signified when scholars "meet in select conferences; they commute between one center and another; they circulate preprints and reprints to each other; and they collaborate in research" (Price 1986, p. 119).

Research into the structure and roles of invisible colleges provides useful insight into the innovative practices of scientists. Findings show the research process to be a largely social enterprise in that an informal network of scientists and their students, organized around an important research agenda (a phenomenon), make crucial decisions (Lievrouw 1990; Teixeira 2011). Indeed, young scientists and graduate students are acculturated into the value of both participating and perpetuating these invisible colleges, what Knorr-Cetina (1999) has famously called epistemic communities, in which members learn or are mentored to see any new technological breakthrough as either arising from within the community or as a result of the invisible college responding collectively to external breakthroughs. The diversity of backgrounds and perspectives brought together through such a community network creates novel opportunities for the development of innovative ideas (Cohendet et al. 2014; Lungeanu and Contractor 2014).

3.2. The Roles of Non-Human Elements in Networks

Studies drawing on concepts of social networks and invisible colleges provide insight into the formation, structure, and value of informal networks for innovation processes. However, these studies provide little guidance regarding the roles that non-human actors may play, even though we know that networks of innovation often imbricate physical artifacts and concepts (Garud and Rappa 1994; Hargadon and Sutton 1997). Moreover, innovation scholars have long recognized that non-human actors can play a role in innovation networks (e.g., in the forms of patents and grant funding) (Murray 2002).

One form of these non-human actors are objects: "something people act toward and with" (Star 2010, p. 603). What we learn about a particular action or goal can be translated into functions that an object provides to those who use it. In this way, objects "embed knowledge" (Bechky 2003). This means that objects can shape other actors' interactions in innovation work (Humphries and Smith 2014; Kallinikos et al. 2012). There are multiple ways of theorizing objects that lead human actors to act toward and with them (Ewenstein and Whyte 2009). There is also consensus that objects can take both symbolic and material forms (e.g., Bechky 2003; Knorr-Cetina 1997; Miettinen and Virkkunen 2005; Nicolini et al. 2012; Scarbrough et al. 2015). Weick's (1979) characterization is that an object lies in two intersecting arenas: the mental and the physical. The interplay of these two arenas is captured by the notion of enactment through which actors "actively put things out there" (1979, p. 165).

In innovation, concepts are fundamental instances of symbolic objects, as ideas and knowledge are crystallized (Hargadon 2003; Van de Ven et al. 1999; Verganti 2008). As such, concepts facilitate innovation processes by providing a means for connecting human actors (Hargadon and Sutton 1997; Islam et al. 2016). Concepts, and the evolution of people's understanding of them, evolve as part of the network of relations (Weick 1979). In addition, as a part of the network, concepts can be combined together and become new concepts in their own right. Therefore, innovation processes can be described as both the (re)discovery of pre-existing concepts (Harper 1996; Johnson and Gustafsson 2003; Knight 1971), and the creation of new concepts through the combination and transformation of existing concepts and resources (Garud et al. 1998; Lyytinen et al. 2016; Venkataraman 1997).

Material objects can also be conceived of as exerting some form of agency on others—through having or lacking certain material properties (Jarrahi and Nelson 2018). These properties, inscribed by designers (often, but not always, intentionally), influence people's interactions with innovative products (Garud and Rappa 1994; Orlikowski 2000). As such, these material objects become artifacts that embody both physical traits and shared meanings (Boxenbaum et al. 2018; Orlikowski 2006). Artifacts provide embodied knowledge and can be active participants in a relational network, serving as the impetus for human actors to connect with, make sense of, and ascribe both meaning and action to these artifacts (Garud and Gehman 2012; Van de Ven 2005). Seen this way, relationships among actors are mediated by artifacts (Garud and Karnøe 2003; Timmermans 1999).

All this noted, there remains a lack of conceptual clarity about the role of objects, and much of the innovation literature considering networked innovation processes fails to explain both how artifacts and innovation concepts embody knowledge and how the presence, features, and uses of these artifacts and concepts might connect people and the exchange of knowledge through innovation networks (Scarbrough et al. 2015). More specifically, studies of networked innovation have been stymied by two conceptual limitations: (1) that objects as non-human actors disappear from the analysis, or (2) these objects are treated as exogenous variables and not as participants (Contractor et al. 2011).

Some innovation research has sought to conceptualize objects; but, in doing so, treats these and social networks as two separate entities. In this conceptualization, non-human actors are exogenous factors influencing the functioning of the social relations (e.g., Landry et al. 2002; Quan-Haase and Wellman 2004; Westergren and Holmström 2012). For example, by examining patterns of R&D collaborations in the context of the semiconductor manufacturing industry over time, Kapoor and McGrath (2014) explain how the emergence and evolution of deep ultraviolet manufacturing technologies have shifted the types of interactions among different types of R&D actors, positioning these as forces shaping networks but not as participants.

Treating objects as existing outside the relevant social relations has been called into question by scholars who highlight the mutual constitutions of objects and social networks (e.g., Akrich 1992; Latour 2005; Pickering 1995; Scott and Orlikowski 2012). Rather than advancing causal relationships among the innovation network and objects, these scholars conceptualize non-humans as endogenous factors and treat both objects and human actors as members of the network (Kallinikos et al. 2012). Doing so helps us to examine how both types of actors may play a role and how the network structure emerges from the complex interactions among various human and non-human actors (Contractor et al. 2011). This is particularly relevant to understanding objects' roles in innovation as a diversity of technological breakthroughs, visions, and concepts pave the way for further innovation, and it is increasingly difficult to single out isolated relationships between single objects and an innovation network, which may leave the interactions among multiple human actors and objects as well as the objects themselves by the wayside.

Seen this way, the structure of an innovation network should be conceptualized as a broad *sociotechnical assemblage*, something that encompasses ongoing interactions among human and non-human actors (de la Bellacasa 2011; Licoppe 2010; McLoughlin et al. 2000). To advance this perspective, we draw on tenets of ANT to theorize on the constituents and structure of a sociotechnical assemblage formed around the tabletop computing research community. We argue that presenting both human and non-human actors as members of the sociotechnical assemblage allows us to capture the contribution of individual researchers, organizing visions, innovation concepts, and artifacts.

4. Actor Networks and Conceptualizing Innovation as Relational

The conceptual basis for this study builds from work in the sociology of science that conceptualizes networks as including both human actors and non-human objects (i.e., artifacts and concepts) (e.g., Latour 2005; Suchman 2007). Scholars in the sociology of science are concerned with the reciprocal relationships among social, political, and cultural structures; science practices and scientific research; and technological innovation (Callon et al. 1986). One of the goals of this effort is to open up the "black box of technology" for sustained analysis, by paying due attention to the process and contents of the constituent technologies (Akrich 1992; Law and Bijker 2000). This perspective draws the scholar's attention toward analyses focusing on how a technology is constructed during research, development, and innovation in relation to human actors' interactions (Geels 2004).

One of the most useful analytic approaches for analyzing sociotechnical assemblages is actor-network theory (ANT) (Latour, 1987). Emerging in the early 1980s, ANT was first used to help explicate the process of knowledge creation in science and technology development. The ANT approach stands apart from earlier approaches to conceptualizing sociotechnical assemblages, such as the social construction of technology (e.g., Bijker 1997; Woolgar 1991), whose focus typically discounts traces of, or roles for, technological agency (Sawyer and Jarrahi 2014). Over the past 30 years, ANT has been translated and taken across the social sciences because of its conceptual power. Our purpose in drawing on ANT for this study is to contribute to the discourse on innovation networks, not on advancing ANT, so our review of ANT is limited to specific elements of direct relevance to this study (readers looking for a more in-depth treatment of ANT are encouraged to begin with Latour, 2005).

What makes ANT a valuable conceptual frame for the study of innovation networks is that it makes no *a priori* analytical distinction between the social and technical (Latour 1987; Latour 1999). Rooted in a "ruthless application of semiotics" (Latour 1999, p. 3), ANT's first premise is that entities have no inherent qualities: they acquire their form and functionality only through their relations with other entities. This relational premise means that concepts of context cannot be distinct from an actor-network—what one might characterize as 'context' or 'aspects of the situation' matter in ANT only if there is a relationship developed among entities of interest. That is, ANT is neither contextual nor a-contextual: the actor-network is both local and distant. The relationships among entities of interest, actions, and locations are the focus and substance of ANT.

Actor-network theory is premised on the concept of generalized symmetry (e.g. Callon 1986; Callon 1999; Latour 2005). As Latour (1991, p. 129) maintains: "Rather than assuming that we are dealing with two separate, but related, ontological domains—objects and organizations—we propose to regard them as but phases of the same essential action." The concept of generalized symmetry allows both human and objects to be "actants" (Akrich 1992). This formulation provides the mechanism to overcome the limitations of most network-centric research on innovation processes as it expands the notion of a network to reflect both the technological capabilities and the knowledge residing within (or embedded into) objects (Geels 2004). As such, ANT offers a means to conceptualize objects as members of the sociotechnical assemblage (Genus and Coles 2008).

An actor-network is constructed through the enrollment of allies (other actants) into a network by means of negotiations. These actants can be both human and non-human (e.g., computer-systems) (Geels 2004; Hanseth et al. 2004). The process through which actants interact with one another to build or to transform the network is called *translation* (Harrisson and Laberge 2002). In translation, one group of actants may try to advance certain agendas, mobilize resources, and translate the interests of others in hopes of engaging them. That is, the mobilizing group seeks to "problematize" or frame issues in such a way to encourage new participants to translate interest into action. According to Callon and Latour, the focal actor is "any element which bends space around itself, makes other elements dependent upon itself and translates their will into the language of its own" (Callon and Latour 1981, p. 286).

Much of the explanatory power of ANT lies in the concept of translation, the processes through which a heterogeneous network is constructed and stabilized. Translation illuminates the dynamics by which focal actors recruit other actors into a network. Translation encompasses how actors are drawn in, enrolled, and mobilized based on a problem that seems pivotal to them—the movement from problematizing to enrollment.

Using concepts of problematization, translation, and enrollment, ANT complements innovation research that draws on social network concepts (e.g., Dhanaraj and Parkhe 2006; Obstfeld 2005; Owen-Smith and Powell 2004; Van de Ven et al. 1999). It does so by helping to explain how a heterogeneous network comes together over time, how both objects and people become members of the network, and how these translations and enrollments help to shape the structures of an actor-network (Geels 2010).

This noted, ANT's notion of network is metaphoric. The social network perspective treats the network as the social structure of relationships between social actors, whereas ANT employs the notion of network primarily to describe an ontology of relationality by focusing on "constitutive intertwining and reciprocal inter-definition of human and material agency" (Pickering 1995, p. 26). This relational ontology between objects and humans, and their agency (what they can achieve), are seen as interdependent, situated, and emergent (Genus and Coles 2008).

To account for the role of non-humans in the network, ANT uses the concept of inscription as a process whereby translations of actors' interests are embodied into objects. That is, translation presupposes a material into which it is inscribed: text, software, and the like (Callon 1991). And, ANT posits that through concepts of symmetry and translation, networks can both enhance innovation processes and constrain them by circumscribing the kinds of innovations produced, their subsequent interpretations and their final uses (Callon 2002).

In order for the actors to secure the support of others they must make themselves indispensable. Callon (1986, p. 201) calls this an "obligatory passage point." In a network of relations, one or more actors present themselves as both indispensable and representative of others' interests—they are "delegated." As different actors will have a diverse set of interests, the stability and irreversibility of a network hinges on the ability of delegated actor to translate (re-present or appropriate) others' interests to one's own (Ciborra 2000). Therefore, a network's stability and sociotechnical order are not given; they are continually (re)negotiated through a social process of aligning interests. During negotiations, a *moment of translation* unfolds where a possible ally is recruited because the solution to their problems appears only viable via participation in the actor-network (Garud and Gehman 2012).

In ANT, a network is considered stabilized—it is able to exist over time—only if translation is successful (Latour 2005). More precisely, achieving network stability means that participants have been enrolled; their interests have been translated into relations through the network such that this action is irreversible (Latour 1987). The translation is irreversible when an actant's investment in the network reaches a point at which withdrawal would be unthinkable. The durability of a network is matter of the robustness of the translation. Moreover, once stable (or made durable), the members of the actor-network are available to be mobilized—to turn their attention and resources to pursue shared actions.

Building on the premises of ANT, we advance the concept of a sociotechnical assemblage. In doing so, we explicate how humans (e.g., tabletop researchers and scholars) and non-humans (e.g., visionary concepts, and prototypes) become enrolled in the tabletop actor-network to produce innovative outcomes. We specifically highlight the roles played by humans in problematizing compelling visions, and by non-humans in connecting humans, translating the interests of others and enrolling them in the actor-network. In what follows, we describe how the sociotechnical assemblage came into being and evolved after a series of translations, through which multiple actants enrolled in the actor-network and helped advance it. Then, in Section 6, we draw out ways through which key human and non-human actants facilitated the enrolment and translation process, including visions formulated and propagated by visionaries, and promising technologies and concepts that instantiate these visions.

5. Data Collection and Analysis

Our approach to constructing an actor-network of tabletop computing builds on three overlapping data collection efforts. We began with an initial exploratory examination of the intellectual community. This involved investigating relevant websites, scholars' work, and other sources (e.g., press releases, technical magazines, and marketing brochures) to help us better understand the key concepts, technologies, and participants and their relationships relative to tabletop computing.

To do this, we pursued iterative data analyses. This began with tracing leads and connections several steps away from our entry point (following the actant), and continued through to the level of closure we report on here. Due to the ever-always-emergent nature of the community and the actor-network, we knew no clear boundaries could be drawn. Instead, our objective was to obtain an overall sense or gestalt of the intellectual space which was created by the interaction of core actants (Latour 2005). So, our empirical data and analysis are not aimed at depicting "the one true network" (Gruber and Wallace 1999, p. 93): we focused instead on characterizing the basic structure, evolution and recurring elements of the actor-network.

We mapped the relationships among key players across several distinct periods. We began this mapping using data from an extensive, iterative, bibliometric analysis. To do this, we identified the publications that help define this intellectual space through backward chaining of the papers that were being cited. The result was that we found 145 papers that were core to tabletop computing. Careful readings of these helped us identify specific concepts and representative or enabling technologies that underlie scholarship around tabletop computing.

To develop our actor-network, we treated concepts and specific technologies discussed in these paper(s) as possible network members—to make these patterns visible for analysis. We also used co-authorship relationships among individuals from different organizations as proxies for relationships among actors. This synthesis of published documents offered insight into the material contributions of members of the tabletop community, and the underlying organizing concepts that serve as the structural components of it (Zuccala 2006).

In addition to the bibliometric analysis, we documented specific forms of collegial interactions among researchers. We defined collegial interactions as social ties forged between two researchers as a result of their participation in leadership roles at the same conferences or workshops (Zuccala 2006). Price (1986) highlights the importance of collegiality in scholarly communities, noting that "people claim to be reasonably in touch with everyone else." They "meet in select conferences and commute between one center and another" (p. 119). To get at these collegial relationships, we examined the interactions among researchers in conferences and academic workshops relevant to tabletop computing. For example, we linked individuals if they served as co-chairs for a conference track or co-organizers for a workshop, or if they collaborated through adviser-advisee or mentor-intern types of relationships.

The third data collection effort relied on interviews of key informants. Following the initial round of data collection and analysis, we conducted interviews with seven key informants identified based on the bibliometric analysis. The open-ended interview protocol included questions about: (1) the role and contributions of the interviewees, (2) specific individuals, concepts, and technologies they saw germane to the development of the community, (3) the salient visions that drove the intellectual work in this space, and (4) the evolution of the relationships over time. And, we used maps that we had made of the tabletop community's network to facilitate our discussion with the informants. In doing this, we asked them to corroborate the existence and roles of particular individuals, concepts, technologies, organizations, and seminal events that we had identified. The interview data provided us with a greater understanding of the underlying nature of the interactions (i.e., collegiality), and more "interpretive and heuristic" insight into the structure of the community (Lievrouw 1990, p. 68).

Data analysis was structured by the conceptual vocabulary of ANT, providing us with a basis for capturing the sociotechnical dynamics of the community over time. Specifically, we focused on the enrollment of participants, efforts to support translation, and the obligatory passage points that helped to define when the tabletop actor-network entered a period of stabilization. We also sought evidence of mobilization—when the actor-network was active and directed toward some common interest. What comes from this effort is a narrative description of 15+ years of the tabletop computing actor-network, a summary of which we present below.

6. Findings

Given the goals of this paper, we focus on the structural elements of tabletop computing's actor-network, emphasizing the participants (actants), relations, and some of the mechanisms that serve to structure the actor-network. This is laid out in the first subsection. Analysis leads us to highlighting results regarding five aspects of the tabletop innovation actor-network. In the second subsection, we discuss each aspect of this analysis in more detail using the conceptual language of ANT.

6.1. Tabletop Computing's Network of Innovation: 1995–2012

We report on tabletop computing's innovation network for the period 1995 to 2012. We stopped data collection in 2012, when Microsoft PixelSense entered the marketplace, as noted above. Deciding on when to start was more of a judgement as no single date or action defines when the tabletop computing actor-network springs to life. This noted, analysis of the interview transcripts, field notes and bibliometric data suggested to us that by early 1995 a number of scholars who shared some overlapping visions of computing and whose work was drawing on one another began to be more proactive about getting together. This seems to be driven in part by several papers being published in the early 1990s. For example, Wellner (1993) advanced a prototype that involved both object and touch recognition; Carter (1993) provided a useful summary of relevant work on touch; and Fitzmaurice and colleagues (1995) reported on their "digital desktop" technology prototype that embodied touch, location and object concepts brought together.

In the actor-network, we include institutions, individuals, concepts, and technologies as actants. The links between them come from analysis of published work, review of secondary documents (e.g., conference program membership, and workshop attendance), or explicit discussion in an interview. ANT does not conceive of core or peripheral actants, but it does emphasize following the actor of interest, which we used to decide on representing direct relations to the concepts, people, or technologies that drove the network.

Based on our reading, we saw the concepts and technologies in Fitsmaurice et al.'s (1995) paper as the initial actants to follow. Interviews with participants and paper citations helped made clear that a group of scholars had begun to cite each other and interact more regularly because of shared interests in collaborative interfaces for computing. These early and informal interactions put these scholars in the position to serve as boundary spanners among different communities and, in doing so, helped each other to see that they were forming a community of scholars around tabletop research. This coalescing happened because of social connectivity, driven by shared visions of ubiquitous computing.

Before 1995, there was no clearly identifiable venue for meeting about and sharing tabletop computing–related work. Researchers who later formed the core of the community tended to engage in their own scholarly communities. For example, by nature of their work and discipline, researchers working on computer vision (computer technologists) did not feel the need to meet or directly connect with people working on groupware protocols (individuals who mainly identify themselves as CSCW researchers. Likewise, those working on interactive displays were aware of these spaces, but focused on their own work (e.g., Ishii and Kobayashi 1992). These and other clusters of what were to become tabletop computing remained largely disconnected—a common occurrence in innovation (e.g., Uzzi et al. 2007).

Between 1995 and 2000, the number of papers that explicitly focused on horizontal interfaces, shared computing displays and other common terms grew modestly (see Table 1 and also Müller-Tomfelde and Fjeld 2010). For example, Stafford-Fraser and Robinson (1996) shared their "BrightBoard" prototype, and this spurred a number of additional studies and prototypes that sought to overcome limitations with interaction and text handling (see Brown and Robinson 2000). Likewise, Streitz, et. al. (1999) and Rekimoto and Saitoh (1999) had published reports of their work on collaborative interaction space and augmented surfaces.

As shown in Table 1, by 2000, the number of core human participants had doubled; many others (typically graduate students) were also partly involved. What demarcates the boundaries between the core and periphery of this actor-network is the observation that the researchers who form the core have been mobilized by a small number of shared ideas about what might be possible for collaborative computing interfaces. In addition, core human members of this community came from a broad spectrum of backgrounds and from multiple existing academic communities. The period 1995 to 2000 is also notable, compared to the other periods represented, in the relatively small growth in numbers of concepts and technologies. It may be that this reflects the need for people to become enrolled, even as the concepts and technologies are acting on them to get together. That is, the relatively smaller number of concepts and technologies reflects the relational draw they exerted on the humans relative to drawing enrollment.

Networks' core elements	**1995**	**2000**	**2005**	**2012**
Core individuals	14	28	46	50
Institutions	11	15	23	26
Concepts	30	41	71	85
Technologies	12	20	48	72

Table1: Growth of tabletop computing's actor-network, 1995-2012

As summarized in Table 1, by 2005, the core group of tabletop scholars numbered 46, more than three times the number in 1995 and 50% more than in 2000. By 2012, this group had grown to 50, with most of the growth due to graduate students opting to stay on because their scholarly interests were now focused into this space. In addition, by 2012, another 45 scholars had some involvement in the tabletop community and we see these as peripheral members in that they had a few connections to select members of the network.

The period of 2000 to 2005 also saw rapid growth in the number of concepts and technologies involved in the actor-network. This growth reflects scholars, concepts, and technologies becoming enrolled into the actor-network. This was the period of what Müller-Tomfelde et al. (2010) call 'enabling technologies,' during which, the actor-network's focus was on advancing concepts and prototypes relative to multi-touch and representative displays. This required substantial efforts to build out and share software and to explore their uses. Taken together, this growth helps make clear this was a period of rapid innovation and coalescing the network.

From 2005 to 2012, we see the network's growth shift from enrolling people to enrolling technologies, along with a steady growth in concepts. As Buxton (2016) reflects, this was a period of active prototyping and many of the papers of this period reported on user studies, explorations, and additional design ideas (concepts) that were being embedded into existing technologies (prototypes). Perhaps this shift in the actor-network, from concepts and people towards technologies, represents a movement from basic research towards commercial production.

Our understanding of this actor-network comes in part from working backward through the corpus of relevant papers and other materials (such as conference programs and web presences) to follow concepts and ideas that brought these scholars together. Doing this illuminated the importance of ideas and concepts advanced by both Douglas Engelbart and Mark Weiser. Douglas Englebart (1962) wrote about augmenting human intellect as a conceptual framework aimed at articulating a vision, entreating its importance, problematizing it, and making a strong case for different groups of computing researchers to rally behind his vision. These writings served as a springboard for scholars of human–computer interaction. Through this work, Engelbart laid out the ideals for information environments and envisioned computers as generic adjuncts to humans. This vision was formulated before the advent of personal computers, when people could only use computer through intermediaries. Englebart sought to sell his vision to other computer scientists, coining the concept of *smart space*—a 'seamless' integration of people, computation, and physical reality (Englebart and English 1968).

Weiser's interests were related to the social norms of computers and their interfaces , famously asserting "the most profound technologies are those that disappear" (Weiser 1991, p. 66). What he presents as profound technologies "… weave themselves into the fabric of everyday life until they are indistinguishable from it." In his vision of ubiquitous computing, the delivery of computation should be transparent. Weiser's team at Xerox PARC worked on a variety of computational devices including Tabs, Pads, and Boards, along with the underlying infrastructure. These devices were developed to represent his vision (Ishii and Ullmer 2008).

This vision of ubiquitous computing challenged early tabletop researchers. It problematized direct existing technological constraints and potential areas of development for future technological innovations. For example, Weiser maintained "…neither an explication of the principles of ubiquitous computing nor a list of the technologies involved really gives a sense of what it would be like to live in a world full of invisible widgets." (Weiser 1991, p. 103); he also used plausible futures to advance his ideas. For example:

Sal awakens: she smells coffee. A few minutes ago her alarm clocker, alerted by her restless rolling before waking, had quietly asked "coffee?", and she had mumbled "yes." "Yes" and "no" are the only words it knows. Sal looks out her windows at her neighborhood. Sunlight and a fence are visible through one, but through others she sees electronic trails that have been kept for her of neighbors coming and going during the early morning. Privacy conventions and practical data rates prevent displaying video footage, but time markers and electronic tracks on the neighborhood map let Sal feel cozy in her street. Glancing at the windows to her kids' rooms she can see that they got up 15 and 20 minutes ago and are already in the kitchen. Noticing that she is up, they start making more noise. At breakfast Sal reads the news. She still prefers the paper form, as do most people. She spots an interesting quote from a columnist in the business section. She wipes her pen over the newspaper's name, date, section, and page number and then circles the quote. The pen sends a message to the paper, which transmits the quote to her office . . . (Weiser 1991, p. 103)

Nearly 30 years later, some aspects of this tale have become real, others continue to guide current scholars advancing affective, ubiquitous and tabletop computing. For example, Hiroshi Ishii, a professor at MIT Media Lab, was drawn to tabletop computing because of Weiser's vision. Ishii notes, "*For us, the most important thing is the vision, the philosophy, the principle. I've never been driven by science or engineering. Technology gets obsolete in a year, and applications get obsolete in 10 years. But vision driven by art survives beyond our lifespan*" (Chandler 2009).

These shared visions were often translated into specific technological prototypes, and this was increasingly the case, as the actor-network grew denser, with more attention paid to turning ideas into technology. Turning a vision into a technology required the hard work of translating ideas into artifacts: these "technological concepts" became tangible, specifically formulated to encapsulate existing computational capabilities. Therefore, technological concepts became an important means of connecting people. For example, North et al. (2009) drew on and extended the early work on displays in tabletop interfaces that were generated by Wobbrock et al. (2009) regarding the nature of gesture recognition.

Embedding visions into a specific technological form typically required extensive re-imagining and encouraged new discourses and the creation of new concepts—doing the work of taking an idea and turning it into a prototype required extensive learning and articulation of design choices. For example, Scott et al. (2004) drew on concepts of territoriality, orientation, and partitioning from studies in other workspaces to generate new ideas about group dynamics in collaborative tabletop workspaces. Their work resulted in the conceptualization of territoriality on tabletop interfaces, which can be taken as a new concept. As a result, Scott et al. (2004) refined and augmented some initial, sparse conceptual work through a process of prospecting, mining, refining, and demonstrating how territoriality could be translated into touch-based screen features.

Technological concepts and the specific forms they took were one type of artifact bound up in the tabletop actor-network. In saying this, we conceptualize artifacts as encompassing both written documents and their technological forms. That is, published papers and prototypes are the salient constituents of an artifact in the tabletop community. To be involved in the actor-network of tabletop computing, the vision, the technological concept, and other forms of artifacts had to exist to have some sort of reality (even if this reality was often digital).

The importance of artifacts means that undocumented prototypes, or papers in which a design or feature is proposed but not instantiated, do not become part of the actor-network—as there is no actant who could participate. Therefore, while people might read about an idea, or hear about a prototyping effort, these were transient elements—hearsay—until the ideas or prototypes could be published: only then did artifacts have a chance to join. For example, Andrew Fentem began working on multi-touch interfaces in 2002. However, he seems not to have published his work in academic venues. Therefore, his work has not been cited. Since the work is not generally known in the tabletop computing network, it has little influence on the evolution of the network (Buxton 2016).

All the technologies we identified in tabletop computing began as prototypes; most never became products even as they remained core actants. For example, SecondLight, developed in Microsoft Research's Cambridge (UK) Laboratory, relied on rear-projection vision systems, but also allowed extending the interaction space beyond the tactile surface (Izadi et al. 2008).

At a more detailed level, prototypes are combinatorial as one can be incorporated into another or developed further into commercial products. These non-human actants remain in the network however, because of the relationality. The new prototype that arises from such an incorporation is related to these actants. Even as the number of people in the core of the actor-network doubled from 2000 to 2012, the number of technologies (prototypes and proofs-of-concept) more than tripled.

This helps make clear the non-human actants—visions and technological concepts—were central members of the tabletop computing community. Two points need be made on this simple insight. First, the non-human actants are two-thirds of the total number of nodes in the 2012 actor-network. Even as we know this simple depiction is a proxy for the reality of an actor-network, it is representative of the more complete picture that including visions and technologies in the network can provide. Second, the non-human and human actants exist *in relation* to one another (Law 1992). Data show that core members have both direct connections with each other and connections through visions and technological concepts. Peripheral and tertiary members often have one or the other form or relationship. That is, peripheral members may have a personal connection to a core member—perhaps through other work or social engagements, or to a core vision—perhaps through shared interests in some vision such as ubiquitous computing.

What the papers and interviews show in terms of humans' relationship with non-humans is that tabletop computing scholars typically pursue one of two roles: technology builder or concept researcher. Some pursue both. The main contribution of a technology builder is an artifact or prototype. To wit, Shahram Izadi (then of Microsoft Research) notes, "*My research is very applied, meaning I like to build and play with diverse interactive technologies, all in the name of science*" (Izadi 2012). Concept researchers focus on investigating different technologies relative to their usability and interaction with humans and the ways in which these uses relate to outcomes. The major contributions of these individuals' research are the empirical data and conceptual understanding of these technologies' uses. For example, the conceptual work on groupware for tabletop technology, advanced by Stacey Scott (then at the University of Guelph) and her colleagues extended the understanding of territoriality in collaborative tabletop workspaces (e.g., Scott and Carpendale 2006; Scott et al. 2003). This conceptual work guided technology builders with their design.

Analysis of the tabletop communities' growth makes clear graduate students play central roles in connecting scholars both to each other and to new technological concepts. We note that graduate students do so because they move around via summer internships in research labs and because of their relocations from university "A" to "B" to pursue their master degrees, doctorates, and later postdoctoral studies. In doing so, the students provide the social connectivity that creates both more and stronger links among current network members. These moves also serve as the means to share knowledge and strengthen or expand social connections. While many graduate students leave the tabletop computing community upon graduation, some do not. This is a source of much of the community's growth over the years we focus on in our analysis.

Data also show that the institutional and organizational affiliations of the scientists involved in tabletop computing are connected to the actor-network. For example, in the 1990s, the University of Toronto employed Bill Buxton and through him, was a key institutional player. When he left Toronto, its institutional presence faded. In contrast, Microsoft was a marginal player at first, but Andy Wilson—who has been instrumental in developing PixelSense—leveraged his position in the interorganizational tabletop community to advance their product. Some organizations, like the United States' National Science Foundation (NSF), were very important secondary players because the resources from grants allowed people to do the research, get together in workshops and conferences, and support graduate students to move around for summer research. As such, funding sources like the NSF, the Mitsubishi Electric Research Labs (MERL) and Microsoft were critical members of the tabletop computing actor-network, even as this membership was always tied to individuals and their host institutions through granting mechanisms. This larger institutional and organizational milieu is, as organizational scholars note, the space in which the network of relationships among people, visions, concepts, and artifacts exists (Chatterjee et al. 2002; Swanson and Ramiller 1997).

6.2. Participation and Enrollment

Data show that by 2012 the tabletop community's core comprised nearly 50 researchers, with many others on the periphery. In addition, based on the review of their publications, core members of this community come from a broad spectrum of backgrounds from multiple academic communities beyond tabletop. We demarcated the boundaries between the core and periphery with the observation that the researchers within the core have been mobilized by a small number of common visions. These common visions (e.g., augmented reality and ubiquitous computing) bring people together.

Analysis suggests one role that these actants serve is knowledge brokers (Brown and Duguid 1998). As knowledge brokers, the researchers in the core have access to, and the ability to more easily share, diverse bodies of knowledge with each other. For instance, Andrew Wilson, a central actor in tabletop computing's core, has extensively drawn from John Barron's (and his colleagues') work on image processing (e.g., Barron et al. 1994) to construct his tabletop prototypes (e.g., Wilson 2005; Wilson et al. 2008). However, John Barron remains on the periphery, as he is not directly connected to tabletop computing research, even though his work has been drawn on by many of its core actors. Core players often translate concepts found in another research community, reframing these imported concepts and knowledge into their work and, doing so makes them more accessible to the other core and peripheral members of the tabletop's actor-network

Enrollment in the tabletop computing community manifested itself when: (1) individuals frequently assembled in tabletop computing–relevant workshops and conferences (e.g., the International Workshop on Horizontal Interactive Human Computer Systems and the International Conference on Interactive Tabletops and Surfaces[7]); (2) these individuals drew upon the work produced within the tabletop community—explicitly noting core concepts in (the title of) their publications (e.g., tabletop computing, horizontal display, and interactive tabletop); and (3) these individuals directly engaged in the development of related prototypes and products (e.g., Microsoft's PixelSense).

Data make clear that the community's intellectual boundary remained permeable—as we would expect given the literature on epistemic communities and invisible colleges. Core researchers' social ties with scholars outside the tabletop community kept them from becoming over-invested in one research enterprise, exposed them to a wide variety of worldviews, and linked them to other sources of potentially relevant knowledge. Moreover, peripheral members – who were even more strongly connected outside the tabletop community – helped tabletop community scholars to draw in ideas from related disciplines and scientific communities.

6.3. Non-Human Actors and Artifacts

Our analysis of the tabletop computing community illuminates the roles of visionary concepts and specific technologies that are often embedded into specific prototypes. Both are actants in the terminology of ANT. Visionary concepts and technologies draw the attention of scholars within the community because they enact ideas of great interest: they are proofs of concepts, instantiations of ideas, and working examples of possibilities. In saying this, we conceptualize artifacts as encompassing both written documents and their technological forms. That is, published papers and prototypes are the salient constituents of an artifact in the tabletop community. It is not possible to have an undocumented artifact, or to have a paper in which a design or feature is proposed but not instantiated.

6.3.1 Visionary Concepts

Relative to the role of visionary concepts in helping draw together the tabletop computing actor-network, ANT provides us the concept of translation (Latour 2005). The visionary gurus in tabletop computing succeeded in *problematizing* their visions, posing them as problems around which a new research enterprise should be built. The visionaries then began persuading other actors that such problems are significant enough to dedicate resources to their solution. As such, these actants contributed to the translation process through which 1) significance of the problems was reaffirmed, and 2) participation in the actor-network was constantly presented as a viable solution.

The translation process of these visions of tabletop computing has become so successful that they found their way into popular culture. For example, a version of ubiquitous computing interfaces was featured in the 2002 movie *Minority Report*. John Underkoffler, a student of Ishii at MIT Media Lab, coached actor Tom Cruise to gesture in front of a blank screen to simulate the interactions with a three-

[7] http://iss.acm.org

dimensional gesture display (Chandler 2009). Then Pete Thompson (the general manager of Microsoft's tabletop computing group) referred to the movie in the debut of Microsoft's tabletop product (then called Microsoft Surface): "It will feel like *Minority Report*… futuristic—but it will be here this year" (Perenson 2007).

Visionary concepts act on tabletop computing scholars, serving to both motivate and guide them. For some tabletop computing researchers, visions are more motivating than are technological implementations. For example, Ishii notes: "*for us, the most important thing is the vision, the philosophy, the principle. I've never been driven by science or engineering. Technology gets obsolete in a year, and applications get obsolete in 10 years. But vision driven by art survives beyond our lifespan*" (Chandler 2009). This is in line with the contention of ANT that, within actor networks, some actors undertake more salient roles, in terms of mobilizing resources, advancing innovative agendas, and translating the interests of other parties and enrolling them (Callon 1991).

Within the tabletop actor-network, these visions effectively turned into obligatory passage points, which both represented and translated the interest of other actants. That is, without these compelling visions, other human and non-human actants (technologies that materialize the visions) would not have been mobilized and enrolled into the actor-network. The longevity of the tabletop actor-network and its persistence over the years is a testament to the stability of the translation process since the interests of different actants were effectively translated into relations within the actor-network.

6.3.2 Technologies (and Prototypes)

Technologies differ from visionary concepts in that they are more tangible: specifically formulated to encapsulate existing technological capabilities. A technology embodies a concept (or, more typically a collection of concepts) that is (are) realized in a digital, or digital-material, artifact. For example, Microsoft's PixelSense and Mitsubishi Electric Research Laboratories' (MERL) DiamondTouch both embody the technological concepts of multiple users and gesture recognition. Yet, PixelSense uses optical sensing to deliver multi-touch gestures whereas DiamondTouch uses capacitive sensors to achieve these goals. These technologies' functionality are related to the specific concepts on which they are based, the scientists who enable the technology to act (through design and development), and the other technologies that may guide or rely on this particular form. This set of relationships makes it difficult to understand any technology independent of the relations to concepts, human actors, and other technologies.

We treat the broad category of technology and the specific instance of a technological arrangement – the prototype – as conceptually similar. Clearly, prototypes take on powerful roles, acting on the network to guide and motivate. DiamondTouch and Pixelsense are central actors in the 2012 network: many of the concepts, other technological actors, and active researchers are drawn together in relation. More broadly, and taken together, visionary concepts and technologies are elements of the tabletop computing actor-network.

6.4. Human Actors

Both visions and technologies exist *in relation to* people, their efforts, and the social processes they pursue in the same way that people in this community exist in relation to the visions and technologies. What binds all this together are social processes that include knowledge-intensive activities such as community-building activities, pursuit of scientific research, technological design activities, and product development. These social processes involve tacit knowledge that is embedded in people and manifested in their concepts and technologies – and difficult to codify (Powell 1991).

Any one individual's knowledge within the tabletop community represents both past and present linkages to other people, concepts, and technologies they have connected with over time. These individuals are not impartial conduits as "they become embroiled in diverse, partisan, and increasingly embedded ways" (Van de Ven 2005, p. 369). Any one individual's engagement in the construction and refinement of technological innovations and innovation concepts assumes several different forms (i.e., shared projects, technology design, and paper co-authorship). Through these shared practices, the knowledge brought in from other communities is localized and appropriated in the quest of a shared vision.

In addition to advancing concepts and building technologies, human actors work to span community boundaries, doing problematization and translation work. Each time one of the tabletop scholars joined a new organization, they brought their knowledge and connections to the new organization. As such, these people are in a position to become translators or boundary spanners. For example, Bill Buxton, at the time a principal researcher at Microsoft Research, exemplified this role by connecting researchers from the University of Toronto, Microsoft Research WA, Microsoft Research UK, and Mitsubishi Electric Research Laboratories, all places where he had worked. As he moved, he drew in more people to tabletop computing. Additionally, when he left each organization, that network connection waned—along with the possibility of continuing to do problematization and translation.

6.5. Organizations

Data indicate that some of the organizations involved in the actor-network of tabletop computing found ways to take advantage of the innovations arising from the actor-network. Certainly, Microsoft's Andy Wilson—who has been instrumental in developing PixelSense—leveraged his position in the interorganizational tabletop community to advance their product. Likewise, the United States' National Science Foundation (NSF) and Natural Sciences and Engineering Research Council of Canada (NSERC) provided relatively modest funds (in support of graduate students and early research) and deserve a great deal of credit for doing so. Other companies like Sony and Mitsubishi played important roles, but seemed involved only to the extent that they had researchers in their employ who were active members of this community.

Some institutions took very little value from participation, possibly because this participation was only via researchers who worked at that organization. For example, the University of Toronto, the institutional home to Bill Buxton for many years and an early and important source of resources (in terms of time, students, and research support) to the tabletop community's growth, fell out of the tabletop computing community when affiliations changed. Likewise, NYU became a part of the actor-network only because several members of the community joined the faculty.

We began by noting that products are typically developed within institutions, and these become a "black box" to members of the larger innovation network who lie outside that organization's formal boundaries. While product development greatly depends on the participation of core actants who are enmeshed in the community, the processes and decisions that take visions, concepts, and other knowledge and turn them into a product are properties of that institution, not the community. What this quick aside about organizations suggests is that there are other ways for organizations to be involved, though only some realize the value of the involvement.

7. Discussion and Implications

Building from the findings, we highlight four implications for discussion: (1) advancing the sociotechnical assemblage as the locus of innovation and, in doing so, showing how ANT can contribute to studies of innovation, (2) specifically highlighting the roles played by artifacts as part of an innovation network, (3) clarifying the trans-institutional structure of innovation, and (4) providing practical guidance for advancing innovation practice.

7.1. The Sociotechnical Assemblage as Locus of Innovation

Data suggest that a sociotechnical assemblage of humans and non-humans is the locus of innovation in the tabletop computing community. We have drawn on ANT's concepts of translation and enrollment to explain the process through which scientists, concepts, technologies and formal organizations come together. In doing so, we have highlighted that innovation, through a sociotechnical assemblage, is a function of its whole structure and is not reducible to either human or non-human actors. Most scholars have moved past hero-based accounts of innovations to see these as products of networks of people and institutions (e.g., Hargadon and Sutton 1997; Singh and Fleming 2010). We suggest that the next step is to be more attentive to the centrality of concepts and artifacts as key players in innovation networks, and we see this as the next step (e.g., Garud and Karnøe 2003; Hohberger et al. 2015).

What is visible in a sociotechnical assemblage are the relations among human actors, visions, technological concepts, and other artifacts, showcasing the ways in which innovation across the community is enacted. For example, researchers at the University of Toronto's Input Research Group drew from several technological concepts from the tangible computing community to develop a "graspable user interface" by building "bricks technology" (Fitzmaurice and Buxton 1997). This, in turn, was drawn into tabletop computing's gesture recognition. The technological concept and artifact originated outside of the tabletop community but was seen and brought into the network where it inspired a new technological concept of direct relevance to tabletop computing.

We know that innovations draw together technological concepts and affiliated technologies and this is difficult to dissect in some sort of linear fashion or easily attributable "giant step" (See also Hargadon 2003; Henderson and Clark 1990). For example, to implement multi-touch visual systems, researchers within the tabletop computing community developed both front-projection and rear-projection techniques. Approaches based on front-projection (e.g., Wilson 2005) tended to capture users' interactions more effectively on the tabletop, as the camera points directly at the display, although occlusion of the display by the users' hands can be an issue (Müller-Tomfelde and Fjeld 2010). On the contrary, approaches based on rear projection (e.g., Han 2005) place the camera underneath or behind the tabletop, reducing gesture interference. However, because these approaches project onto a diffuse surface material, the may make sensing objects more difficult (Izadi et al. 2007).

7.2. The Roles Artifacts Play

Artifacts appear from our analysis to be more important than is articulated in many organizational and social analyses of innovations (e.g., Barlow et al. 2006; Ferlie et al. 2005; Swan and Scarbrough 2005; Van de Ven and Rogers 1988). We observe that the technologies and visions often served as bridges or hubs which link or unite individuals. This both amplifies and extends Garud and Karnøe's (2003) provocative insights into the ongoing negotiation regarding the implications and meanings of evolving concepts and technological artifacts being defining activities in the innovation network. These non-human actants, traveling across time and space, can partially overcome the limitations of humans. For example, within the tabletop computing actor-network, this characteristic of innovation concepts has enabled Izadi and his colleagues (2007) to build on the concept of *asymmetric interactions*, which was articulated by Yves Guiard in 1987 (see Guiard. 1987). Likewise, Jun Rekimoto's (2002) development of the SmartSkin interactive surface helped drive the development of similar technologies in US-based tabletop research.

The agency of non-humans is realized both when they enable other actants and when they constrain actions (Jarrahi and Nelson 2018). The concept of *inscription* provides a frame for defining the material affordances that are initially inscribed by developers (be they visionary gurus, technology builders, or conceptual researchers) into a set of key visions, technology artifacts, or concepts. Inscription implies that these non-humans carry forward the developer's beliefs, social and economic relations, previous patterns of use, legal limits, and assumptions as to what the object is about (Akrich 1992).

Inscription means a non-human can become an actor of its own. As Akrich (1992) notes, a large part of the work of innovators is that of "inscribing" their vision of the world in the content of the new non-human actant, which greatly shapes the potential relationship between it and its surrounding actants. For example, DigitalDesk (Wellner 1993) was a groundbreaking technological prototype (that was never commercialized) which married two concepts: object recognition and touch recognition (direct interaction). As such, it serves as both a great inspiration and basic prototype upon which several future studies and tabletop technology developments build (e.g., Carter 1993; Stafford-Fraser and Robinson 1996). The prototype, however, was not capable of performing accurate optical character recognition and this limited how the prototype was put into use by other researchers (Brown and Robinson 2000).

While material boundaries inscribed into a non-human help frame the range of possible ways to engage it, other actants can enact them in unexpected ways based on their context, individual preferences, motivations, and the like. What this means is that inscription can guide researchers to join or use the technology or concept in a way that is in line with the designer's intention; many researchers actively seek to inscribe their own vision and interests into the artifact. For example, researchers at Dublin City University developed their own prototype, called Físchlár-DiamondTouch (Smeaton et al. 2006), based on DiamondTouch (a multi-touch input technology that supports multiple, simultaneous users developed by MERL). The new prototype worked within the supports and constraints of the original prototype, but featured new material properties (e.g., a set of new interface interactions to support collaborative search interactions).

7.3. The Trans-Institutional Structure of Innovation Networks

Findings make clear the sociotechnical assemblage, the actor-network of tabletop computing, extends beyond any one organization's boundaries. It is therefore neither crafted for, nor controlled by, any one organization or specific organizational mandate. Moreover, resources for the tabletop computing community (most commonly, funding) came from several participating organizations (e.g., the NSF, Microsoft Research, MERL, and others). Yet, the basic concepts and core technologies are not connected to any one organization. Even projects solely supported under auspices of one organization may have contributors from other organizations. Moreover, it appears that individuals are more central than organizations, something that becomes evident when people change jobs. For example, Jeff Han chose to leave New York University (NYU) to develop his tabletop product in a spin-off company—Perceptive Pixel. Han was still a key member of the network, but his home institution changed, and NYU is now mostly disconnected from the tabletop computing community.

More broadly, analysis showcases three aspects of institutions in the network of innovation. First, institutions are omnipresent: institutional affiliations are part of what each human participant brings to the network. Consequently, even as people change jobs and institutions, these institutions remain related, a step outside of the actual network of innovation. Second, institutions provide resources: legitimating participation, supporting student interns, providing for studies, technology development, and enabling travel and interaction.

The third institutional insight that arises from our analysis is that some institutions are quite attentive to their roles. For example, MERL was quite involved—until they were not. The United States' National Science Foundation (NSF) and the Natural Sciences and Engineering Research Council of Canada (NSERC) both funded researchers to pursue concepts and technological artifacts, supported students, and enabled travel in pursuit of their mission to advance science and train the next generation of scholars. Some institutions invested in individuals even though they made no effort to leverage the tabletop computing network (e.g., University of Toronto and NYU). Others made explicit decisions to leverage, fund and encourage the network (e.g., the NSF). The omnipresence and interests of these various institutional players becomes the backdrop, the whitespace, across which the network of innovation emerges and is sustained. Institutions have played critical but not always attentive roles.

7.4. Implications for Practice

What also comes clear from this work is that conceptualizing innovation as entwined with a sociotechnical assemblage is useful for describing the emerging structure of many innovation networks because it draws attention to the informal patterns of interpersonal relationships and collaboration among researchers who are connected to one another based on a shared vision and the use of various concepts and artifacts. The structure of this sociotechnical assemblage has particular implications for the creation and dissemination of innovative knowledge.

Building from this analysis and discussion, we address two implications for innovation practices that ANT guides us to see. First, the analysis makes clear the importance of internships and graduate student experiences as ways to embody, enact, and connect networks of relations and encourage institutional participants and significant actors in an innovation network. Graduate students both represent and expand social connections for their adviser(s), creating relations. Furthermore, given the relational arrangement among objects, concepts, and people, graduate students' movement creates more connections. What we observe over time is the steadily increased network density, due in large part to graduate students being given opportunities to situate themselves into the community.

Second, and building from the observation that institutional participants are both omnipresent and yet are often passive or tertiary members of innovation networks, we encourage leaders in these organizations to consider how to better leverage the epistemic communities in which their people are enmeshed. This may be as simple as encouraging more thoughtful institutional participation through supporting meetings among scholars, providing internship experiences, and enabling sharing of technological artifacts, concepts, and visions (which sometimes seems so contrary to the financial goals of patent exploitation and the fears of intellectual property leaving the firm). The opportunity for greater institutional participation and increased value for both the innovation network and these omnipresent players is an opportunity space where few models exist (e.g., 3M, IDEO) (Garud et al. 2011; Kelley 2001).

To this point, data indicate that some organizations found ways to benefit from their employee's participation in the tabletop community's actor-network. These organizations found ways to leverage the community's knowledge, typically relying on concepts and technologies. Second, these organizations have hired people who were already engaged in basic research in order to incorporate their expertise and innovation know-how. As an important example in the tabletop computing space, Microsoft employed many of these interns and researchers (e.g., Katherine Everitt, Daniel Wigdor, Bill Buxton, and Shahram Izadi). In this way, benefits accrue to Microsoft even though it was relatively new to the space (in effect, it started working on tabletop technologies after 2001). By hiring in researchers who had long been engaged in the community, Microsoft was quickly able to develop tabletop commercial products. Microsoft's approach also makes clear that in order to gain value from their members' informal network connections, the host organization must have both the intention to act and internal capabilities (absorptive capacity) to do so, as passive reception of ideas rarely leads to innovation (Gebauer et al. 2012; Najafi-Tavani et al. 2018).

8. Future Work

We have used actor-network theory to help us illustrate that innovations emerge from a network of human and non-human actors that we refer to here as a sociotechnical assemblage. Drawing on data about tabletop computing, we show that the innovation network was emergent and comprised visionary concepts, technological concepts, human actors and institutions. On this last, we note that some of these organizations benefited from the network; others did not. Data make clear this network, this sociotechnical assemblage, emerged from a range of distributed efforts, rather than being intentionally orchestrated by some central actors who recruited others (Dhanaraj and Parkhe 2006; Human and Provan 2000). This diffuse and emergent structure yields what Hughes (1983) calls *momentum*, something that organizational leaders may want to consider as they create organizational competencies and seek to acquire value-adding resources.

Our approach to this research creates two opportunities for future work. The first opportunity reflects the consequences of our research design. We studied a single case, which is useful for theorizing but not for theory testing (Eisenhardt and Graebner 2007). While many of the practices and events observed in this study have been echoed in other accounts of innovation (e.g., Hargadon and Sutton 1997), outcomes from this study are specific to the particular context of this community. This noted, our findings help to advance current theorizing on innovation processes. What is now needed is study of other contexts and innovation networks, as the innovation practices examined in this research do not seem to be entirely idiosyncratic.

The changes in the network over the 17 years of this study highlight the importance of time. Historically, innovation scholarship has suffered from a lack of a process-oriented understanding of how innovations unfold (see Hughes 1983, p. for more details). Thus, most contemporary models of innovation under-emphasize the temporality of innovation. Likewise, many network studies tend to represent cross-sectional snapshots rather than attend to the evolutionary nature of innovation processes (Parkhe et al. 2006). To date, few studies have adopted a process view to capture temporal changes in networks (e.g., Burkhardt and Brass 1990; Doreian and Stokman 1997; Hite and Hesterly 2001)[8].

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[8] We echo Van de Ven (2002), Monge and Contractor (2003), and the National Research Council (2003) that indicate studies of innovation too often fail to directly address temporality. In addition, we note that the growth of networks is a central issue for much of the research in complexity theory, though their research findings are difficult to assimilate into the existing literature on innovation and social networks. For more on this see Amaral and Uzzi (2007).

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