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Digital Mesh: On the Rise of Mesh Computing

Completed Research Paper

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Abstract

The proliferation of connected devices into every corner of the planet gives rise to a world of mesh computing. In this conceptual paper, we analyze the implications of this emerging computing environment for information systems (IS) research. We first discuss how mesh computing can be related to but differs from other views of computing that emerged along the history of IS research. We then advance a provocative perspective for studying the uniqueness of mesh computing—digital mesh. We conclude with a discussion of the opportunities and challenges for future IS research. The discussion deals with the need to expand IS use research from effective use to generative use and IS design research from substantial architecture to processual architecture. These shifts, however, come with new research challenges for which we propose process structure analytics as a valuable methodological solution.

Keywords: Mesh computing, digital mesh, generative use, processual architecture, process structure analysis

A Motivational Example: Life in a World of Mesh Computing

Following brief gentle vibrations on the bedside table, an iPhone starts to play a beautiful chime at an increasing volume that progressively brings you back to consciousness. It is a frigid winter morning, but the bedroom is at a comfortable temperature. Just minutes ago, the Nest thermostat turned on the heating and adjusted the room temperature to your preference that it learned through the past days. "Hey Siri, do I have any appointments today," you ask. "You have one appointment at 8 AM at the office," the phone replies. It seems to be a busy morning. You jump out of bed and say, "Alexa, play some mood-lifting music from Apple music." As the music flows, you walk to the bathroom and step on a Withings scale. You open an application on the phone, which displays a colorful page with health statistics, including your weight on the scale, sleep quality, glucose, blood oxygen levels, heartbeat rate, and many more from your Oura Ring. Everything seems normal. You start brushing your teeth with an electric toothbrush until the phone beeps, telling you that you have brushed every tooth. Hearing the winter wind howling outside, you realize the car must be freezing inside. "Hey Siri, warm up the car," you say while quickly washing your face and getting dressed. Before running out the door, you realize the curtains are still closed, and the lights are on. Therefore, you shout, "Alexa, I am leaving!" As the door closes, a Roomba vacuum crawls out of the corner to wipe up the floor.

As soon as you stand in front of the office building, you feel your Galaxy watch buzzing. The location triggers a calendar notification, reminding you of the 8 AM meeting. There are only five minutes left. You tap your Mi band on the card reader at the gate. As the gate slides open slowly, you dash into the building, skip the elevator, and run up the stairs. As soon as you reach the office, several messages pop up on your watch screen, congratulating you for the completion of today's exercise goal and being ranked in the top five percent among your friends. After an exchange of pleasantries, you invite your visitor to have the meeting over coffee. At the café, you tap the POS with your watch for payment. Today's coffee tastes different, rich, and sweet. You take a photo of the coffee bean bag exhibited at the counter with the Amazon mobile application, which directs you to the coffee bean's webpage. You place an order and request it to be delivered to your home. Your visitor wants to walk you through some presentation slides on Box. However, the café's network connection is too slow. So, you share your 5G network via the phone. A few hours later, the phone alerts you that someone is lingering at the front door of your home. Clicking the notification banner, an application comes to the front with a real-time video from the Xiaomi doorbell camera. You press the microphone button and ask the stranger what they want. They are from Amazon delivering the coffee beans. You authenticate temporary access to them to drop the delivery in your garage using Amazon Key. As the garage door shuts again, you receive a notification about the delivery's completion and the key's revocation.

Introduction

From futuristic to state-of-the-art to quotidian, it took only half a century for such a scenario to become our daily life. The development of connectivity, sensor, intelligence, database, miniaturization, and battery technologies continuously advances the functionality and mobility of computing devices[1] and propels their hybridization with physical products (Yoo 2010; Wang 2022). As the coinage "Internet of Everything" suggests, it is only a matter of time that whatever we see and touch will attain digital capabilities to compute, sense, and communicate with each other.

This emerging computing environment has important implications for information systems (IS) research. As we have observed over the past decades, the evolution of the computing environment usually evolves our views of computing, leading to IS research innovation. Two works that have exemplified this are "nomadic computing" (Lyytinen and Yoo 2002) and "experiential computing" (Yoo 2010). The former expanded IS research from its traditional focus on intra-organizational use of stationary computers to cross-context mobile use of computing resources. The latter expanded IS research from its traditional stereotypical idea of computers as a "beige box" (Yoo 2010) to the hybridization of computing devices and physical products. Despite their differences in terms of technological artifacts and sociotechnical settings under consideration, the two works and subsequent studies (e.g., Chen and Corritore 2008; Bødker et al. 2014; Prasopoulou 2017) indicate that it is valuable and essential to attend to the evolution of the computing environment, so that IS scholarship remains relevant (Baskerville et al. 2019).

Along the same line, this paper seeks to direct attention to the emerging mesh computing environment. A mesh computing environment not only inherits and pushes computing power, mobility, and hybridization of computing devices to their extreme. It is also characterized by a distinctive new feature, *non-hierarchical interoperability*, that allows heterogeneous computing devices to work with each other without assuming a dominating device. As the motivational example illustrates, computers from different providers can be used in a mixture, in which each device contributes to an emergent use scenario equally. Different from previous research where there is a dominating device that plays a focal role in a prescribed use scenario (e.g., an ERP system as a tool for business operation), the role of a device in mesh computing emerges and evolves on the move (e.g., the iPhone can be both an interface of smart home and a network router).

In this conceptual paper (Gilson and Goldberg 2015), we analyze the implications of this emerging computing environment for IS research. We first discuss how mesh computing can be related to but differs from other views of computing that emerged along with the history of IS research. We then propose a provocative perspective for studying the uniqueness of mesh computing, resorting to Ingold's (2015) thesis of line. We conclude with a discussion of the opportunities and challenges for future IS research. The discussion deals with the need to expand the focus of IS use research from effective use to generative use and IS design research from substantial use to processual architecture. These shifts, however, come with

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[1] This paper uses "computing device" instead of other terms that begin with "digital." The reason is that there are legacy analog computers in use nowadays that contribute to the operation of mesh computing, and novel non-digital computing devices such as continuous variable quantum computers that may participate in the mesh computing environment in the future. "Computing device" emphasizes two aspects of the entities it refers to. First, "computing" emphasizes the activity of data processing. Second, "device" emphasizes that corporeal humans need physical contact with nonmaterial data and nonmaterial data needs material bearers (Baskerville et al. 2019; Faulkner and Runde 2019).

new research challenges for which we propose process structure analysis as a methodological solution.

Evolving Technical Environments Evolves Views of Computing

For elaborating on the idea of mesh computing, a distinction must be made between it and other views of computing that have emerged across the history of IS research: *stationary computing*, *nomadic computing*, and *experiential computing*. We focus on representative papers, as a thorough review is beyond the scope of this paper. The objective here is to clarify the differences between the views and to position mesh computing in the development of IS research.

Stationary Computing

The first view, stationary computing, has existed since the beginning of IS research around the 1960s (Hirschheim and Klein 2012). It emerged under the background of the massive adoption of computers in organizations. This view reflects the idea that most decision-making and operational tasks in organizations are computational in nature, and rising problem complexity necessitates increasing computational power (Simon 1965; Simon 1979). As decision-making and operational tasks in modern organizations become ever more complex, computers have become an indispensable tool for their speedy, accurate, consistent, and durable computing performance that no human can match. Given such a focus on solving complex computational problems, the creation and use of computing devices had for long been focused on building computing resources to a specific functional area where they are most needed, as argued by IT alignment and governance research (Benbya and McKelvey 2006; Clemons and Weber 1990). In other words, the computers are fixed to a predefined site where a particular set of problems happen frequently or are usually brought to—for example, a desktop with accounting software in an accounting department. Stationary computing research proceeds to ask about how to improve computational power, where a computing device should be placed, whether a computing device is well aligned with typical problems in the area that it is located, and who is responsible for channeling issues to a computing device, and the like.

Nomadic Computing

Alongside stationary computing, nomadic computing emerged around the 2000s. This view attends to the emerging computing environment where advancing miniaturization and network infrastructures make it increasingly easier to carry computing devices across different sites while keeping access to powerful computational resources through network connections (Lyytinen and Yoo 2002). This view goes beyond the idea that computational resources must be built in close proximity to a functional area. Instead, it shifts the focus to the temporal channeling and invocation of computing resources through mobile devices wherever a user sees their relevance on the go (Chen and Corritore 2008; Ladd et al. 2010). A typical example is that a sales representative uses a tablet computer connected to the headquarters' business intelligence system to validate a client's price proposal in the client's office, using real-time cost and inventory data. Reflecting such a focus shift from the functionality of a stationary computing device to the mobility of computing resources, the construction and use of digital infrastructures that afford mobility emerged as a central topic in IS research (Ladd et al. 2010; Lyytinen and Yoo 2002). As mobile use is not only shaped by technological features but also depends largely on the decisions and movements of social actors; individual perceptions, team dynamics, organizational processes, and inter-organizational interactions also became essential aspects examined by nomadic computing research (Henfridsson and Lindgren 2005; Ladd et al. 2010; Lyytinen and Yoo 2002).

Experiential Computing

Alongside the previous two views and in response to IS research's overemphasis on work-related computing (Baskerville et al. 2019; Faulkner and Runde 2019), Yoo (2010) proposes experiential computing as an alternative view of computing. This view sheds light on the emerging computing environment, where an increasing number of daily products become hybrid as physical products such as speakers, bicycles, and shoes get embedded with computing devices (Yoo 2010; Harris et al. 2012). In work-related computing, users experience the computing device itself as the end (see Hirschheim 1985)—for example, "this inventory software is easy to use." In contrast, in experiential computing, users sometimes need not pay attention to the device that shapes their everyday experience (Yoo 2010). For example, a user habitually wears their smartwatch without thinking about if it counts their steps; even though they attend to the watch when it alerts them to walk more, they barely associate the experience of a healthier life directly with the use of the device. In other words, the watch—or, more precisely, its computing components—becomes an invisible bearer of daily experience (Yoo 2010). Motivated by such a fusion of computing devices into everyday experience, research is conducted to understand the socio-material complexity and dynamics of how IS transforms larger social contexts beyond work contexts—for example, the entanglement of humans and wearables through daily use (Prasopoulou 2017), or the dynamics of un-reflected use that flows with life versus reflective use with dedicated time (Bodker et al. 2014).

In summary, stationary computing, nomadic computing, and experiential computing together indicate that *evolving technical environments evolve views of computing, which in turn innovates IS research*. The improvement of the computing power of a standalone computing device makes the site of powerful computing resources a place where problems should be brought to, which gave rise to stationary computing research with a focus on functionality. The advancement of the connectivity of computing devices allows a computing device to channel computing resources to the place where problems are encountered on the go, which made for nomadic computing research with an emphasis on mobility. The progressive hybridization of physical products and digital technology enlarges the connotation of computing devices to the affordance of lived experience, which called for experiential computing research attending to embodied experience. Such a historical development, featured by the two pivoting research commentaries (Lyytinen and Yoo 2002; Yoo 2010), supports the argument for the importance of attending to the evolving computing environment for innovative theorization for the future (Burton-Jones et al. 2021). In support of this line of thinking, we next turn to the emerging computing environment—mesh computing, discussing its essential features and distinguish it from the other views of computing.

Mesh Computing

Mesh computing finds its practical ground in technological liberalism and mesh networks. Technological liberalism is an ideology existing since the beginning of the Internet that promotes equal participation in the information economy (see Lax 2001). Mesh networks are a technical foundation that was first proposed in the 1970s for the development of robust wireless networks that could be infrastructure-less[2] (without the reliance on a back-end computing resource, e.g., a server) and fully decentralized (no single network node is prioritized over others) (Bensky 2019; Ramanathan 2018; Ramanathan 2020). This technical idea has been confined to the experimental stage for the past decades for two reasons. The first was technological challenges such as the low computing power of network nodes, the trade-off between range and throughput of wireless connection, and the complexity of access and routing coordination and security. The second is the absence of lucrative and substantial use cases compared to the cost-effectiveness and wide adoption of centralized network technologies. In recent years, technological advancements such as empowered edge (powerful network nodes), wireless protocols (high throughput and larger range), and blockchain (node engagement and regulation) keep rendering the technical challenges irrelevant. Meanwhile, the proliferation of the Internet of Everything offers a fertile ground for profitable and meaningful use cases. Consequently, there has been a burst of ambitious projects in recent years (e.g., Microsoft Mesh and Samsung SmartThings), heralding an age of mesh computing. In what follows, we firstly discuss the essential features and propose a provocative perspective for understanding the uniqueness of mesh computing.

Essential Features of Mesh Computing

The essential features of mesh computing are *functional versatility*, *perpetual connectivity*, *contingent combinability*, and *non-hierarchical interoperability*. These four key drivers influence and enable how computing devices are constructed and used. We see the first three features as advanced levels of computing power, connectivity, and hybridization, and the last as an additional feature. It should be noted that these features have their respective development trajectory that needs to consider the others. However, when all of them come together, they reciprocally enable and shape each other and give rise to mesh computing.

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[2] As discussed later, a more precise way to interpret "infrastructure-less" is the reducing reliance on centralized infrastructures as each connected device becomes a part of the infrastructure used by other devices and meanwhile uses other devices as its infrastructure.

Functional Versatility

Functional versatility means computing devices are capable of collecting, storing, processing, and exchanging diverse kinds of data. For decades, the design of computing devices has been struggling with a trade-off between functionality and size. A computing device requires computing chips for more and better functionality, whereas better and more chips usually take more physical space. In response to this trade-off, on-demand data processing and storage technologies emerged, moving the computing workload to a centralized server (cluster), and leaving minimum data collection, storage, and processing capabilities in the devices on the network's edge (Davenport and Dasgupta 2019). However, as the miniaturization of sensors and computing chips advances, edge devices become increasingly capable of more computing tasks while remaining their original size or even becoming smaller and lighter. Imagine the significant contrast between the 1997 Deep Blue (in the size of two cabinets but only capable of 11.38 GFLOPS) and the iPhone 13 mini (in the pocket-size but capable of 1.2 TFLOPS). As the motivational example shows, even tiny objects like a ring, a wristband, and a watch can nowadays collect and process various physical and biological data. Another driving force for the enhancement of edge devices is the increasing necessity for a shorter response time to environmental triggers. For example, advanced artificial intelligence (AI) chips are embedded in appliances to process users' voice commands and in smart vehicles to detect and react to sudden movements of surrounding vehicles as quickly as possible without the delay of data exchange with distant processing centers. As automation permeates all sorts of work and life situations, there will be more demand for corresponding technological development to make edge devices more functionally versatile to handle diverse types of information (e.g., voice, touch, gesture, temperature, humidity, acceleration, proximity, ambient light, atmospheric pressure) locally and in a highly responsive manner.

Perpetual Connectivity

If a state is perpetual, it "happens again and again and so seems never to end" (Collins English Dictionary). The advancement of wireless communication software and hardware has made it unprecedentedly easy for computing devices to connect with each other for data exchange. Wherever we go in urban areas, there is usually a cellular network compatible with our mobile device (e.g., a tablet computer). If the device cannot access the cellular network directly, it can still access the Internet through hotspots of surrounding devices (e.g., in the motivation example, the visitor's laptop used the host's mobile phone hotspot to use the online service). As more and more devices get embedded with advanced wireless communication chips, not only tablet computers and smartphones but also speakers, televisions, and refrigerators can form a local network and share their Internet connection. A satellite broadband service would most likely be available even in a rural area that does not have cellular network coverage. As the adjective "perpetual" emphasizes, today's network technology has reached a level where the connection is always maintained despite unexpected interruptions. The reach and stability of such connectivity will only increase as earnest projects by digital start-ups and megacorporations (e.g., Helium Network and Starlink) keep bringing network connections to every corner of the globe. In addition, the standardization of wireless communication protocols and the embedment of multiprotocol wireless chips are making the switch to the best available network more spontaneous and less interruptive along with the movement of users. For example, in the motivational example, the smartphone transited from the home network to the mobile network and then to the office network automatically and smoothly. Eventually, connectivity will become truly endless and seamless, available anytime and anywhere users go.

Contingent Combinability

Contingent combinability means any computing devices can be used in combination as a user sees their relevance in the flow of life. The development and standardization of interface protocols, software, and hardware allow computing devices to be combined in various ways (Yoo et al. 2010; Henfridsson et al. 2018). As introduced above, ubiquitous access to the Internet allows computing devices to be used in combination wherever they are. Without the Internet, computing devices can be combined locally using Wi-Fi, Bluetooth, NFC, Z-Wave, Zigbee, and many more. Besides, embedded sensors enable computing devices to generate and exchange information in various forms such as light, sound, and pictures without any network connection. For example, a smartphone can scan a QR Code on another smartphone to exchange contact information. Furthermore, the standardization of digital formats and the convergence of software and hardware platforms (from lower-level BIOS to higher-level operating systems) increase flexibility for arbitrary software and hardware combinations. Even those platforms once known for their closedness are being continuously opened up even for competitors' products and services. As we have seen in the motivational example, Amazon speakers can now use Apple's music service. Furthermore, the combination becomes increasingly intuitive. For example, you can hand off your iPhone's audio to a HomePod by holding the phone over the speaker without going through a tedious setup. Such increasing ease of combination keeps making combinatorial use an essential mode of using computing devices (Henfridsson et al. 2018; Yoo 2010; Yoo et al. 2010a).

Non-Hierarchical Interoperability

Interoperability is "the ability of two or more systems to exchange information and understand that exchanged information" (Hodapp and Hanelt 2022, p. 1). The adjective "non-hierarchical" indicates an emerging direction of the advancement of interoperability in which heterogeneous computing devices can work with each other without assuming a dominating device. This contrasts with the traditional client-server model, where both client and server devices' identities and intended ways of use remain the same as defined by their designers throughout their lifecycle—a client device will always be a client, and a server will always be a server. Action possibilities of client devices come from server devices, which means the client loses most of its value when the server stops serving the client. In this regard, servers are in the most powerful position, dominating the functioning of the computing environment.

However, this centralized model keeps being problematized. The problematization is not only out of functional concerns such as the problem of single point failure and the interruption and delay of distant data exchange. It is also motivated by the ethos of the Internet (Zittrain 2008) and some vanguards' vision for the Internet of Things (Sarma et al. 2000), which both advocate a connected world where every human and thing has the freedom and equality in interacting and contributing to each other. In other words, in the contemporary world, *a computing device increasingly plays a dual role, that it is an invoker of the infrastructure constituted by other devices and an infrastructure for other devices simultaneously*. Although decentralized technologies such as blockchain and swarm intelligence have just started as business trials, they have undeniably demonstrated that equalizing network nodes makes a network much more robust to survive functional disruption and political suppression. This has revitalized technological liberalism, creating a sociotechnical movement sweeping all walks of life.

Distinguishing Mesh Computing

The introduction of the four essential features of mesh computing shows that, like stationary computing, nomadic computing, and experiential computing, it builds on the development of earlier technologies. If so, how is mesh computing different from them? The immediate answer is *mesh computing depends on users' meaning-making to an unprecedented extent*.

In stationary computing, nomadic computing, and experiential computing, the meaning of a computing device is predefined by its designers (Verganti 2017). Take the history of phones as an example. The equivalent of stationary computing is landlines, which designers understand and define as a device fixed to a place that solves the problem of distant communication. The equivalent of nomadic computing is mobile phones, which designers understand and define as portable devices that can make calls anytime and anywhere. The equivalent of experiential computing is smartphones, which designers understand and define as multimedia devices that can exchange all kinds of situated information. Despite the difference in definition, a phone is always understood as a device for communication that solves a communication problem, increases communication mobility, and enriches the communication experience. This "device for communication" meaning is built in by the designers and dominates how the device is used. This meaning stays at the core and remains the same even after the device is retired from the designers' intended use scenarios of making calls and sending messages.

In contrast, the four features of mesh computing relieve the bounding force of the meaning given at the factory. Functional versatility allows a computing device to play multiple functions (Kallinikos et al. 2013; Yoo et al. 2010b). For example, a smartphone can be a digital wallet, a digital camera, a remote controller, and many more. Perpetual connectivity allows the device to cut across different contexts shaping meaning interpretation (Faulkner and Runde 2013; Faulkner and Runde 2019; Kallinikos et al. 2013; Yoo 2010; Yoo et al. 2010b). For example, as a smartphone moves from a tourist attraction to the bus, its meaning shifts from a photographing device to a social networking device. Contingent combinability allows other devices to bring forth some meanings of a device but push back others (Baskerville et al. 2019; Kallinikos et al. 2013). For example, an Apple TV turns an iPhone a remote controller. Non-hierarchical interoperability makes this meaning redefinition bidirectional, as an iPhone can change the meaning of the Apple TV to a presentation display. Although in these cases, the "phone" meaning can coexist with the new meanings, the "phone" meaning may be abandoned in other cases. For example, "cryptocurrency wallet" and "Internet router" can be two meanings for a retired smartphone that emphasize opposing functionality. A dedicated cryptocurrency wallet must be kept away from an always-on Internet connection for security, while a dedicated Internet router must connect to the Internet all the time. Either way, the phone will not be a "phone" again.

The multiple possible meanings mean that the purpose of a computing device is barely complete (Kallinikos et al. 2013). It is situated in the flow of life, appearing and disappearing as life travels through time and space. Such flexibility of meaning-making makes meaning one more critical aspect of computing beyond functionality, mobility, and experience as computing goes beyond intermittent problem-solving events to become an integral part of continuing human life. Figure 1 summarizes the relationship between mesh computing and early views of computing.

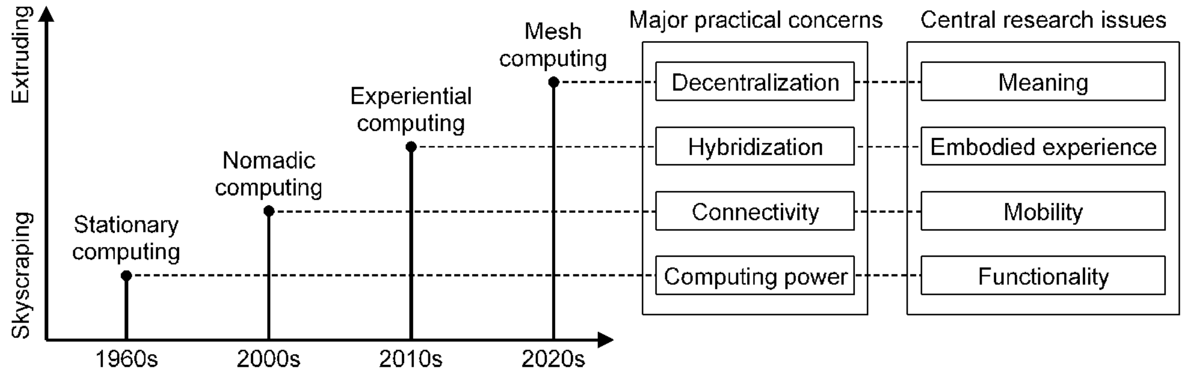

Figure 1. Views of Computing

In response to such an emerging world, IS research should go beyond treating computing as external resources exploited by users' interactions with problems. Instead, they should attend to the historically contingent and situated use along which computing devices are always in the making of life. Although this line of thinking has made its preliminary debut in IS research (Baygi et al. 2021), we will benefit from more comprehensive engagement with it. Currently, we lack an analytical framework, vocabulary, and methods to think, communicate, and examine the uniqueness of mesh computing. To this end, we next resort to Ingold's (2015) thesis for the development of a provoking perspective, followed by discussions of research opportunities, challenges, and methodological solutions.

A Framework of Mesh Computing

Conceptual Foundation: The Thesis of Line

Ingold's (2015) thesis of line advances the idea that the world consists of not only blobs but also lines. A blob is an individual with a boundary, isolating it from other blobs. Blobs may interact with each other in the form of bouncing back each other at their surfaces or dissolving into each other to form a larger blob that has a new surface (territorialization) separating it from other blobs. For this reason, Ingold (2015) claims that there is no life (for both humans and things) in a world constituted only by blobs as "nothing can hold on unless it puts out a line… that… can tangle with others" (p. 3). Lines (e.g., flagella, limbs, paths, and information threads) reaching out from blobs entwine with each other to hold the blobs together despite their surface separation, for example, the crossing of the route of a gatherer and the thread of scent of a fruit, the tangling of fingers and arms of dancing partners, and the interweaving of the footpaths of a hunter and the hunted.

Not only living things but also non-living things can be understood as a phenomenon of line (Ingold 2015). For example, the ground can be viewed as a matrix of lines, and buildings and mountains on it are different knotting lines. If the ground is compared to a handkerchief, building construction is sewing decorating fabrics on it, and mountain formation is creating a heap by squeezing its edges centripetally. The former is skyscraping; the latter is extrusion. Even the buildings can be viewed innately as a result of extrusion in that the construction materials are not produced upon the earth but harvested from it (Ingold 2015). The construction materials are framed and bound by various conceptual (e.g., gravity) and physical (e.g., rebars) frameworks that weave together threads of multiple forces (normal, frictional, tension, etc.) that continue to the ground in a way that can hold the materials together and upward. In this sense, buildings are not essentially different from mountains regarding the formation and sustaining mechanisms. The difference is what tightened the various lines together—a mountain is pulled together by tectonics, while a building is tightened together by lines of humanity (the path of human migration, lived experience, histories of art and science, etc.).

A Line Perspective of Mesh Computing: Infrastructure Extrusion and Digital Mesh

The thesis of line helps attend to the unique nature of mesh computing. Using Ingold's (2015) vocabularies, stationary computing, nomadic computing, and experiential computing reflect the view of blob skyscraping. They often focus on a computing device of interest, separate it from other computing devices, push the other computing devices to the ground as the infrastructure, and then plug the computing device of interest onto the infrastructure. What the computing device is capable of is associated with the computing device itself as it cherry-picks and encases functional and aesthetic components (see Kazan et al. 2018; Svahn et al. 2017; Wang 2022).

Just like blobs can only account for part of the world and skyscraping is innately extrusion (Ingold 2015), stationary computing, nomadic computing, and experiential computing cannot fully explain mesh computing. They prioritize a computing device over others and do not pay enough attention to the increased flexibility and dynamics of how a computing device can assume multiple emergent meanings. In addition, we see in practice not only the creation of infrastructures for a focal computing device (and use case) (e.g., creating satellites, road surface markings, and traffic rules for autonomous vehicles). We also have abundant cases of how a computing device is designed and used to harvest possibilities of existing infrastructures (e.g., postal tracking software making full use of existing GPS fleet tracking systems, Internet, and handheld devices) (Henfridsson et al. 2018; Yoo et al. 2012; Yoo et al. 2010a).

In this latter mode, a computing device at a particular moment of contact with the infrastructure creates a tipping point for unleashing the infrastructure's potential. Such creation and use of a computing device is an instance of the extrusion of infrastructure potential, viz., *infrastructure extrusion* (Ingold, 2015). This mode of creating and using a computing device is particularly relevant to IS research in a mesh computing environment, as a computing device attains a duality in this environment—a computing device uses an infrastructure constituted by other computing devices and meanwhile serves as an infrastructure for other computing devices.

Accordingly, it is questionable to assume users treat the computing device as an entity separated from the infrastructure when they get intimate with the device. Just like a hiker treats a mountain as an extended ground (Ingold 2015), a user treats a mesh computing device as an extended infrastructure. When a user commands "Alexa" to do a refrigerator replenishment routine, it is less likely that they think the speaker itself can check, order, and deliver groceries. It is more likely that they treat the speaker as a touchpoint that lets forth a more extensive set of connected devices (e.g., the whole smart home) that, in turn, comes forth from the Internet of Everything. Although the user may not have all the details in mind, they only pay fleeting attention to where the voice sensor is and understands it as a reaching-out hand of the smart home that will lose its life once detached from the Internet.

In an extreme situation where a computing device is embedded in the human body, the user pays even less attention to the device but much more to the infrastructure. A milder example is the use of a digital watch that reaches out its physical bands and green lights to cling to our arm and blood vessels and eventually the flow of our daily life. In this situation, we do not attend to the watch's every counting of our heartbeats and steps. Instead, we attend more to the smart healthcare and social networking infrastructure, which reaches out its digital treads of signal to entangle computing devices on the deeper side (the smartphone, Internet, other users' data, etc.) (Baskerville et al. 2019; Orlikowski and Scott 2015).

Such a line-based perspective of mesh computing suggests that it is not that the computing device regulates and forces a user's life in a designed direction. Instead, it is the digital device gets tied with other computing devices in the infrastructure by the user's life (cf., Gregory et al. 2021; Berente et al. 2022), and the user's life and the other computing devices get tied together by the digital device. After a long enough duration, the entanglement of the user, the digital device, and the infrastructure attains a degree of durability and forms a recognizable "meshwork" (Ingold 2015, p. 3) where certain types of user life are concomitant with certain collections of digital devices and infrastructures. Living the line of a user, we refer to the touchpoint device and the other devices on the infrastructure side as a *digital mesh*, defined as *a set of connected computing devices that emerges at the contact between human life and the digital world*.

For example, a music lover's life ties together the smart speaker, music library, recommendation algorithm, and other users' data, establishing the computing resources as a digital mesh for digital music entertainment. Meanwhile, the smart speaker enhances the music lover's life by tying the user to the playlists created by the user or recommended by the recommendation algorithm that learns the connection between the user and other users with similar tastes. As time passes, the tie between the user's life and the digital music world becomes increasingly stable. Although the speaker at the contact may have multiple meanings, it is more likely to be recognized as a device that lets out the infrastructure's music entertainment potential that has limitless possible combinations (Yoo et al. 2010; Henfridsson et al. 2018). In other words, the combination is emergent, not pre-designed. Figure 2 illustrates the essential features of a mesh computing environment and how users' interaction with a touchpoint device results in infrastructure extrusion that gives rise to a digital mesh.

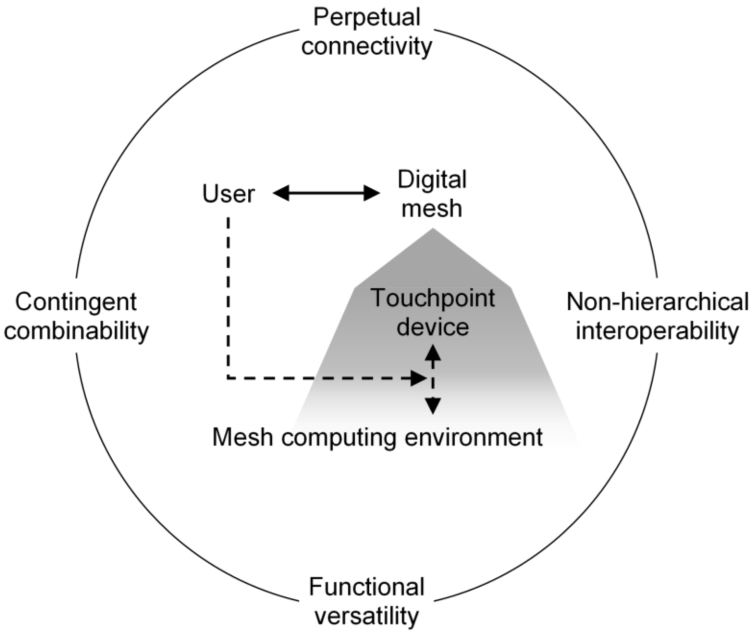

Figure 2. A Framework of Mesh Computing

Implications for Research: Opportunities, Challenges, and Solutions

Our conceptualization of mesh computing suggests research opportunities for extending IS research on use and design. The opportunities come with new challenges for which methodological solutions will be discussed.

IS Use Research: From Effective Use to Generative Use

IS research has long conceptualized use as a "goal-directed activity" (Burton-Jones and Straub 2006, p. 231). Reflecting the alignment view that IT follows businesses (Chan and Reich 2007; Henderson and Venkatraman 1999), it is often assumed that use starts with a given task goal. Users think up ideas about what IT should be adopted and how IT should be constructed or adjusted for achieving the goal. In use, users stand against the IT and travel forth to the goal and back to the IT, which leads to additional ideas to better align the IT for the goal (Burton-Jones and Grange 2013; Baird and Maruping 2021). Such an emphasis on the goal has peaked with the emergence of the theory of effective use, which proposes that use should be effective "in a way that helps attain the relevant goal" (Burton-Jones and Grange 2013, p. 634). In this sense, use, especially effective use, reflects common kinds of activities that Ingold (2015) calls "doing" (p. 125–128). In "doing," actors first project themselves to a preconceived end from which they look back to come up with ideas about how to achieve the end. They then come back and begin implementing the ideas toward the end.

In contrast to "doing," Ingold (2015) sheds light on activities that assume neither a preconceived end to go nor a specified beginning to depart, which he refers to as "undergoing" (p. 125–128). "Undergoing" is the activity of harvesting emergent action possibilities as actors continue their life. Although there will be an end eventually, the end is "a multiplicity of flowing lines of [the actor, tools, and resources] join in a confluence" (Baygi et al. 2021, p. 430) rather than forcing the lines to a preconceived end. In this regard, living is creating, enacting a spontaneous generative history along which actors, tools, and resources do not stand against each other but join each other's life (i.e., development, maturation, and evolution) as a latter moment surpasses an earlier moment along with their lives. Like the above speaker example, it is not that the user forces the speaker only to serve the purpose of music entertainment. The line of the speaker being a music device flows together with the user's life as a music lover. If they lose interest in music, they need not throw away the speaker. It is only their life that flows away from the line of the speaker as a music device. Life may entangle with the line of the speaker in a new direction (e.g., controller of a smart home).

While studying mesh computing, it is essential to understand *use-as-undergoing* because the boundary of a digital mesh is not drawn artificially in advance. Although a user may choose all the devices for their smart home and connect them in a designed way (effective use), the *actual use* may not be the same as imagined by the designers toward the defined end. Given the multiple possible ways of living a life and the smart home does not stop at the building wall but connects to limitless other computing devices on the Internet, new use will always emerge and gives rise to different digital meshes. Therefore, effective use—to use a focal computing device to enable and constrain a life—is only half of the story. The other half is *generative use*—to let a digital mesh emerge as life continues, which is still under-researched.

> *Research Opportunity 1: How does generative use give rise to a digital mesh?*
> *How do human life and digital mesh mutually reinforce each other's agendas?*
> *How do users make sense of a digital mesh at the contact of a touchpoint device?*

IS Design Research: From Substantial Architecture to Processual Architecture

Traditionally, IS design research emphasizes the substantial aspect of IT artifacts (Hevner et al. 2004). Design, as either a noun (i.e., the conceptual plan of the artifact) or a verb (i.e., the process of creating the plan), focuses on an IT artifact's physical and digital properties and capacities. A design articulates every individual part that will be useful and used for realizing the properties and capacities and how they should be architected to work as a whole. Using Ingold's (2015) vocabularies, such a substantial architecture is about the interaction between blobs (the parts, IT artifact, and users). The parts, IT artifacts, and users have different ends; however, they are "joined up" (p. 11) to form a joint history in a way that one denies the directions of others. Often, it is a substantial architecture imposed on users' lives. The problem is no matter how well the architecture resembles a real situation at the moment of design, it will remain the same despite the situation changing as users move along their life.

Alternatively, Ingold (2015) proposes the idea of correspondence, which implies in-betweenness. In-betweenness implies the development of a joint history of the resources, IT artifacts, and users. As discussed above, along with the joint history, users gather possibilities of action on the move. It is not that substantial architecture frames human life, but human life improvises through the mesh computing environment. Rather than the substantial architecture of artifacts, it is the continuity of life and the contingent relevance that users see along with the continuation of the life that decide what artifacts are used and how they are used. In this regard, design is not to impose a material structure upon users' life by fixing an end with a well-planned computing device. Design is to bring out multiple processes of living and give users the possibility to sense and enact the processes as they see relevance along with their life. In other words, the design subject is not the substance but the process. The design process is to create a processual architecture. The research, therefore, should go beyond substantial architecture to explore new guidelines for processual architecture.

> *Research Opportunity 2: How to capture and represent the complexities and regularities of action possibility actualization? How to evaluate the feasibility, viability, and desirability of a processual architecture?*

Research Challenges and Methodological Solutions

The framework of mesh computing sheds light on the possibility of using digital meshes as an alternative unit of analysis. Such a shift comes with multiple research challenges. First, a digital mesh can be boundaryless since everything is connected with everything. Then, where is the edge that we should cut a digital mesh off the whole Internet? Won't such a cut immediately fall in the trap of a blob worldview? Second, due to the intimacy between a digital mesh and a user's life, how can we go beyond describing a specific case to developing generalizable theories (if a study intends so, or a review team requires so)?

The key to dealing with both challenges, we believe, is in Ingold's (2015) arguments that 1) a line of a thing can be viewed as a set of formative events (of development, maturation, and evolution) and 2) similar processes generate similar results. In this regard, we propose *processual biography* as an idea for studying digital meshes, which refers to *the historical process constituted by events that initiate, take hold of, and finish off the digital mesh*. Similar processual biographies should generate similar digital meshes, and similar digital meshes should have similar processual biographies. As users have metal registration of significant events (Ingold 2015), processual biographies can be attained by asking users to retrospect their use (by interviews). It can also be gained by shadowing users' life (by observations).

There have been methods devised and refined for analyzing such data for decades in social studies—sequence analysis (Abbott 1983; Abbott 1990), network narrative (Abell 1993), and event structure modeling (Corsaro and Heise 1990; Heise 1989)—which belong to the same methodological umbrella "process structure analysis."[3] The basic idea of process structure analysis is that social phenomena develop through ordered events (stimuli, memories, actions, etc.) as *earlier events prepare the enabling or containing condition for later events* (Abbott 1983; Abbott 1990; Abell 1993; Corsaro and Heise 1990; Heise 1989).

There are two things worth attention while using the analysis. First, *the order is stochastic, not deterministic* (Abbott 1983; Abbott 1990; Abell 1993; Corsaro and Heise 1990; Heise 1989). Although an event-based description of an observed process suggests a fixed order of stages, the order only indicates a possibility. An observation that "event A is frequently followed by event B" does not mean "A causes B" as the subsequent event is subject to human agency and accidents. Second, *the order matters more than the time*. The event order is a relative order without an assumption of real-time (Abbott 1995). Frequent observations that "event A in the morning" and "event B in the evening" do not necessarily indicate "A has to be in the morning" or "B in the evening,"; but they are plausible evidence that "A happens before B."

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[3] Abbott (1995) refers to the umbrella as "sequence analysis." However, "sequence" implies "sequential" which does not reflect the structural features of network narrative (Abell 1993) and event structure modelling (Corsaro and Heise 1990; Heise 1989). Therefore, we use "process structure analysis" to emphasize that the outcome of the analysis is the structure of a process that can be sequence-, network-, or tree-like.

Without the assumption of deterministic order and real-time, the analytical focus should be on 1) what are the basic events that constitute a phenomenon of interest and 2) what are the structural patterns among the events so that they give rise to the phenomenon.

Given the above discussion of process structure analysis, we can see connections between the methodological ideas and our conceptualization of digital mesh—the phenomenon of interest can be understood as processual patterns. Instead of focusing on what are the static elements that occupy a spatiotemporal spot, process structure analysis enables a study to understand a digital mesh as an enactment and repetition of a process structure that connects action possibilities afforded by contingently joined artifacts. What matters more is the enacted process structure rather than the specific artifacts. This makes it possible for different artifacts to attend the same spot and the same artifact to attend different spots.

Researchers can analyze the similarity of constituent events and structural features to understand a digital mesh of interest or to cluster process structures for differentiating digital mesh categories. The former approach contributes to the knowledge with an understanding of the structural dynamics of a digital mesh, while the latter contributes by identifying new digital meshes. Both can contribute new insights into the question that has been at the core of IS research throughout stationary computing, mobile computing, experiential computing, and now mesh computing—h*ow do IS phenomena unfold as IT artifacts and users entangle* (see Orlikowski 1992; Lyytinen and Yoo 2002; Yoo 2010). Unlike traditional analytical approaches that tend to be bounded by pre-given artifact labels, process structure analysis allows researchers to better attend to users' vocabularies and subliminal use behaviors and how users give new meanings outside pre-given meanings. Of course, process structure analysis has its limitations (Gaskin et al. 2012). However, we argue for using it as a possibly valuable rather than the only approach. In this regard, developing new ways to adapt existing analytical methods for studying digital meshes can also be a promising research direction.

> *Research Opportunity 3: Are there other methods that can increase the credibility and validity of collecting and analyzing data about the emergence of digital meshes that do not have a pre-given boundary and identity?*

Concluding Remarks

This paper aims to call attention to the emerging mesh computing environment. As we have learned during the history of IS research, the research should attend to the evolution of the technological environment as new technological phenomena require expanding our views of computing. Based on this motivation, we have analyzed and identified four essential features of mesh computing: functional versatility, perpetual connectivity, contingent combinability, and non-hierarchical interoperability. The features result in the duality of a computing device as both an invocator of an infrastructure constituted by other devices and an infrastructure for other devices. They also allow a computing device to assume multiple meanings simultaneously. Furthermore, they result in an intimate relationship between human life, the touchpoint device, and limitless other connectable devices. To better appreciate the uniqueness of mesh computing, we propose a provocative perspective built on Ingold's (2015) thesis of line. We advance the idea of digital mesh as a new unit of analysis and prompt a rethink of the nature of use and design to expand IS research from effective use to generative use and from design for structural architecture to design for processual architecture. Meanwhile, we recognize the research challenges due to the uniqueness of mesh computing and the provocative perspective and propose process structure analysis as a methodological solution. We hope our discussion here, along with the new perspective and proposed research opportunities, challenges, and methodological solutions, will motivate a broader interest in mesh computing for a promising direction for IS research innovation.

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