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Four roles of physicality in digital innovation: A theoretical review

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A R T I C L E I N F O

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A B S T R A C T

In this theoretical review, we engage with empirical contributions to digital innovation scholarship to advance our understanding of physicality. Specifically, we develop a conceptualization of physicality grounded in work on the materiality of technology involving two facets: The focus on physicality – an artifact or an activity – and the criticality of physicality when theorizing digital innovation: as a primary or secondary factor. We use this framing to describe four different roles of physicality in the digital innovation literature – physicality as subject, vessel, context, or nexus of digital innovation. Each role of physicality provides a different perspective that, independently or jointly, serves research into emergent topics along the frontier of digital innovation phenomena. This paper thus contributes by consolidating and advancing the theoretical foundation for researchers wishing to attend to varying aspects of physicality when theorizing digital innovation.

Introduction

In their seminal work, Yoo, Henfridsson, and Lyytinen define digital innovations as "new combinations of digital and physical components to produce novel products" (2010, p. 725). Their definition is accepted widely regardless of whether digital innovation is studied as a process (Fichman et al., 2014), an outcome (Lee & Berente, 2012), or both (Nambisan et al., 2017). Thus, a consensus exists that digital innovation goes beyond Schumpeterian innovation (Schumpeter, 1934), due to the combination of digital artifacts – such as firmware, algorithms, and data – as well as physical artifacts – such as electronics, microprocessors, moving parts, and network connectivity (Lyytinen & Rose, 2003; Nambisan, 2013).

Indeed, more and more work on digital innovation recognizes that digital innovation cannot be reduced to the manipulation of digital technology artifacts and its components alone (e.g., Lehmann et al., 2022; Nylén & Holmström, 2015; Priego & Wareham, 2023; von Briel et al., 2018a; Wang et al., 2022). This growing body of work reminds researchers that to manipulate a digital artifact means it must in some way be inscribed onto, contained within, or borne by some physical artifact such as hardware infrastructure or end-user devices (Faulkner & Runde, 2019). Studies with this view advanced the field greatly by documenting forms, processes, and outcomes of digital innovation involving both digital artifacts which are "fungible, ephemeral, and indeterministic" as well as physical artifacts which are "rigid, stable, and tangible" (Yoo et al., 2010, p. 222).

While much of the digital innovation literature acknowledges that digital innovation takes place in a physical world, researchers do not yet share a vocabulary with which to theorize physicality and its role in digital innovation. As a consequence, we fail to distinguish

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digital material from physical matter along "a coherent […] set of properties" (Lyytinen, 2022, p. 19). This lack of a shared vocabulary is most notable when comparing how physicality is defined across studies, what is being studied, and which role physicality takes in relation to digital innovation. As for definitions, some refer to the notion of physical objects as anything which is tangible and persistent in space over time (Priego & Wareham, 2023; Wang et al., 2022). Some define physicality indirectly by contrasting it with digital material, which is described as abstract, semiotic, and virtual, i.e., lacking matter (Baskerville et al., 2020; Lyytinen, 2022). Others do not define physicality at all and instead rely on common sense notions (e.g., Hylving & Schultze, 2020; Svahn et al., 2017). Similarly, the subject of study in work attending to physicality varies, ranging from the physical form of material devices to contain digital innovations (e.g., von Briel et al., 2018a), the interplay of physical objects and their affordances in shaping innovation (Faulkner & Runde, 2019), to digital innovation outcomes enabled by physical objects (Priego & Wareham, 2023). Finally, the role assigned to physicality in digital innovation varies considerably: material objects, their properties, and the manipulation thereof, are varyingly treated as a qualifier of resources to be recombined (e.g., Wang et al., 2022), either as a constraint to innovating within organizations (e.g., Svahn et al., 2017) or as an active element of digital innovation (e.g., Priego & Wareham, 2023). Clearly, physicality is not treated consistently in the literature.

Each of the views above is valuable and productive for scholarship on digital innovation, yet, collectively, the inconsistency with which physicality is theorized is problematic for the field going forward. For instance, inconsistencies in the conceptual foundations can result in the breakdown of a shared understanding necessary to advance theorization of a phenomenon. In the case of physicality in digital innovation, this would not be a mere rhetorical problem, but poses the real risk of incorporating blind spots in the explanations researchers can develop about how digital technology is used to innovate in business and society. This would potentially hinder progress along the frontier of research on digital innovation. Consider how phenomena such as *digitized* 'smart' artifacts, cyber-*physical* systems or Internet of *Things* – all require that digital innovation researchers possess an apparatus with which to theorize digital innovations in a way that does justice to the involvement of both physical as well as digital objects and their manipulation in a material world. Therefore, there is a need to make explicit what role physicality plays in digital innovation, because without a consistent conceptualization of physicality, the explanations of the above phenomena – and many others like them – would be limited.

Against this backdrop, we engage with the role of *physicality* as an important aspect that can further our understanding of digital innovation. We do this through a theoretical review (described in detail below) of the empirical information systems and management literature on digital innovation. We use the theoretical review method (Leidner, 2018; Pare et al., 2015) to first conceptualize physicality and then apply this conceptual lens to identify variations in the treatment of the idea in the literature. Guided by the question "*what is the role of physicality in the digital innovation?",* our review complements recent digital innovation research efforts on physical artifacts and activities (e.g., Lehmann et al., 2022; von Briel et al., 2018a; Wang, 2022; Lorenz et al., 2024).

Theoretical review

With the goal to advance the foundation from which scholars can theorize physicality in digital innovation research, we conducted a theoretical review (Pare et al., 2015) using a systematic search approach (Webster & Watson, 2002). Theoretical reviews are appropriate tools to summarize empirical and conceptual work on emergent topics which, in order to advance, require the revisiting of their theoretical foundations (Leidner, 2018; Webster & Watson, 2002).

Theoretical reviews often aim at structuring, interpreting, and classifying past work with the aim to enable further theorizing in a field of inquiry. To that end, such reviews are often *specific* (Leidner, 2018) in that they do not claim to summarize a body of work in its entirety. Instead, they seek to engage deeply with the subset of work that is most relevant for the review of a specific theoretical idea in order to advance theorizing. As we outlined above, we argue that the digital innovation literature is at a point with respect to physicality where such a foundational theoretical review is necessary to advance work in the domain.

Specifically, we employ the theoretical review to consolidate how physicality has been treated across the body of empirical work on digital innovation. We focus on empirical contributions because it is in the collection and analysis of empirical data that researchers have to confront the role of physicality in their work – implicitly or explicitly. The conceptual digital innovation literature already provides a rich vocabulary with which to speak about physical and digital artifacts in principle (e.g., Lyytinen, 2022; Yoo et al., 2010). Empirical work, on the other hand, has to come to terms with digital innovation in the physical world and address its implications to digital innovation in actuality. Therefore, we focus on the review of empirical work to address physicality – defined in detail below – in relation to digital innovation. The goal of this approach is to consolidate past work and to articulate the different roles physicality can take in digital innovation research. By pointing out how studies individually and collectively attend to notions of physicality when theorizing digital innovation, we approached the literature hermeneutically with the goal to solidify its foundation and to offer guidance for future work in this space (cf. Rowe, 2014). We next describe the implementation of the review methodology.

Review methodology

We implemented our theoretical review via the following four steps. In step (1), we iterated between developing an initial conceptualization to frame physicality. In step (2), we used this conceptualization to guide a systematic literature search to scope the studies selected for review. As is typical for theoretical reviews, these two steps were iterative such that studies that surfaced through early literature searches informed the development of a conceptual frame which, in turn, helped refine the final search parameters. We embraced these iterations and followed the guidance by Schultze (2015, p. 183) to "continue theorizing throughout the review process [to] achieve the higher levels of abstraction" necessary for developing theory through reviews. Despite this non-linear aspect of the review, we report steps (1) and (2) in sequence for readers' benefit. After the final search was performed, in step (3), we engaged in an in-depth analysis of relevant literature using the conceptual framing. Finally, in step (4), we synthesized our findings into four different roles of physicality in work in digital innovation. Fig. 1 visualizes the steps of our theoretical review. We summarize steps (1)-(3) in further detail first, before highlighting the results of the review synthesis in section 3.

Step 1: Conceptual Framing: Physicality and Digital Innovation.

The digital innovation literature has long recognized the role material properties – physical and digital – play in realizing digital innovation (e.g., Jonsson et al., 2009). Nevertheless, physicality is often dealt with implicitly and with some variation in the digital innovation literature. In order to identify and analyze past work, we developed an initial analytical device to provide a consistent and useful conceptual foundation for the review of existing work. Our analytical device conceptualizes two facets of physicality, artifacts and activities, resulting from exposing the etymological roots of the term *physicality* to the work on materiality of technology.

When it comes to the etymological roots, the term *physical*, generally refers to *phenomena perceived through senses* (OED online, 2023), originating from the Greek *phúsis*, referring to *nature* as it relates to both *being* as well as *becoming*. Greek philosophy differentiates *physis* (what is nature) from *technē* (art; what is made by intent). Since Aristotle, the term *physics* is used to refer to the science of studying *space, time, matter, and motion* (Cornford & Wicksteed, 1939). These four terms – *space, time, matter,* and *motion* – are the cornerstones of a conceptualization of physicality since they capture any object in reference to its spatiotemporal context (Yoo, 2010): physical matter is defined by "having spatial attributes such as shape, volume, mass, and location" (Faulkner & Runde, 2019, p. 6), that can change over time. This understanding also forms the foundation of our conceptual framing.

We draw on the rich vocabulary in the literature on the nature of digital technology as human-made artifacts (Baskerville et al., 2020; Ekbia, 2009; Kallinikos et al., 2012; Leonardi, 2012) to develop and ground our analytical device. This work is generative to the understanding of the properties of human-made objects – digital and physical – by attending to their materiality via the trifecta of the concepts *matter, form, and function* (Kallinikos, 2012). The general thrust of this work is that materiality conditions the way any object is perceived, designed, or used. Therein, *matter* describes the material properties of an object that are the result of its constituent elements. Bit strings, for instance, imply properties of editability and programmability of digital elements while atoms determine properties such as volume, mass, shape, and density of physical elements (cf. Priego & Wareham, 2023). Next, the materiality of objects is conditioned by their *form*, i.e., the purposive arrangement of matter in a specific pattern (i.e., a design). Lastly, *function* describes an object's capacity to perform tasks or afford interaction. Jointly, matter, form, and function allow one to make statements about the materiality of an object in its context and, by extension, the physical materiality of digital innovations.

The ideas above ground an understanding of physicality in the existing literature and differentiate physicality by two facets: an *artifact* – i.e., any human-made object[1] – and an *activity* i.e., any manipulation of an artifact in its spatiotemporal context (Yoo, 2010). While both artifact and activity are commensurate with the view that objects are tied to spatiotemporal context, they emphasize different notions of physicality. The first facet, *artifact*, articulates the notion that human-made objects – digital or physical – perform functions as the result of arrangement of matter into a form that affords interaction. Physical artifacts in their spatiotemporal context are thus objects characterized by their purposeful *being in space* – an artifact that is "manifest in and of the everyday world" (Dourish, 2001). The view of artifacts as designed objects underline that they are enduring, lasting, and fully present; their physical properties make them observable at any point in time (Faulkner & Runde, 2019; von Briel et al., 2018b). Such view mirrors the IS field's immense interest in studies of technical artifacts that make up IT systems (e.g., Orlikowski & Iacono, 2001), determine their use (e.g., Jonsson et al., 2009), and aggregate to entire infrastructures (e.g., Tilson et al., 2010).

The second facet of physicality, *activity*, extends this line of thought by emphasizing objects' *changing with time*. Activity refers to manipulating an artifact in the sense of altering its form or function (Yoo, 2010). This notion emphasizes changes to the state of an artifact in space, thus making artifact changes (i.e. an activity) perceptible over time as events or processes (Faulkner & Runde, 2019).

Implied in this conceptualization of physicality is a conditional relationship of necessity between an artifact and activity. An artifact needs to be present for an activity to occur as any activity includes an artifact; e.g., interacting with an object that possesses a definite position in time and space or manipulating a digital representation by means of passing programming instructions to a computing device. Any such interaction with an artifact is material since any activity is conditioned by the make-up (matter, form, function) of the artifact involved (e.g., Jonsson et al., 2009).

Equipped with the vocabulary to ground physicality in materiality, we now turn our attention to the relationship between physicality and digital innovation. Given that any digital artifact must be inscribed onto a physical device to occupy some position within the world in order to make interaction possible and in turn be valuable (Faulkner & Runde, 2013, 2019; Yoo & Euchner, 2020), we argue that physicality is relevant to digital innovation by conditioning the ways artifacts can be interacted with. In other words, design, use, or manipulation of any digital artifact must account for the physical artifact to be "of this world": digital artifacts allow certain actions while disallowing others as a function of the attributes of its physical bearer (Faulkner & Runde, 2019) – be it hidden or visible.

The relationships between matter, form, and function substantiate our view on materiality and allow theorists to make statements about the physicality of artifacts and activities with respect to digital innovation (see Fig. 2 below).

As such, materiality can be expressed as the relationship between matter and form, as matter is arranged into a specific pattern or structure which confers the artifact's form (represented by the arrow labeled "Arrangements" in Fig. 2). Variation in these

[1] we focus on the notion of artifacts as human made object rather than objects in general to reflect the focus on digital innovation, which involves the technological artifact at its core (Fichman et al., 2014; Yoo et al., 2010).

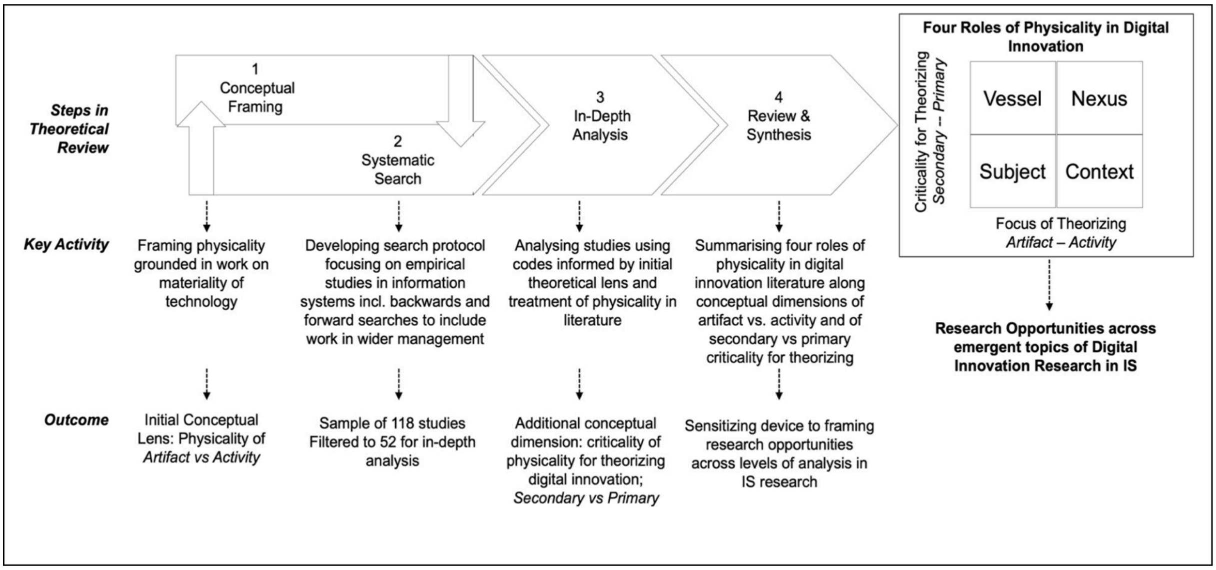


Fig. 1. Visual Representation of Review Implementation.

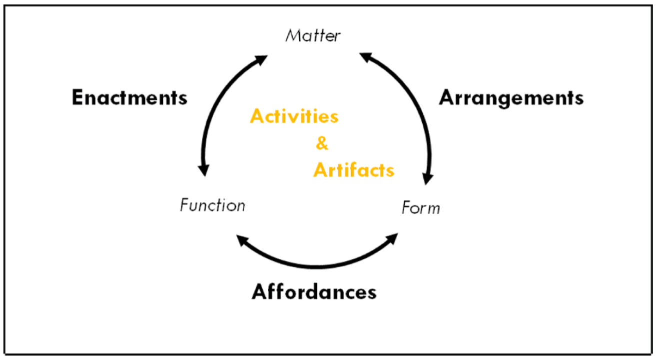


Fig. 2. Relationships of Matter, Form, and Function.

arrangements – i.e., the same material arranged into different forms – can result in fundamentally altered or novel artifacts. Second, materiality may be articulated through the relationship between its form and function, as the specific form can afford potential interactions that can be useful within a given context[2] (Yoo, 2010) (represented in Fig. 2 by the arrow labeled "Affordances[3]").

For example, carbon atoms can be arranged in different patterns that result in forms with distinct properties; for example, graphite is soft while diamond is hard. These forms can afford different functions, such as graphite being used as lubricant or in pencils, and diamond being used in cutting tools or jewelry.[4] The physicality of an artifact thus determines how and which functions it affords in a given context. Some materials cannot be arranged into a desired form; for instance, while carbon atoms can be arranged into short fibers, they cannot be arranged into longer cables without an additional coating of other materials. Similarly, sometimes the potential function of an artifact is not afforded in a given context, such as a machine requiring electricity to function. This relationship holds true for digital artifacts as well. On the one hand, data is generally considered homogenous in its representation through 0′s and 1′s; the

[2] We acknowledge that the industrial practice of linking form and function often draws heavily on symbolic designs (i.e., UX/UI designs incl. icons, buttons, interfaces, digital representations, etc.,). As such, how an artifact's form is organized and relates to a function is often only communicated to the user through visual cues. We thank one of the anonymous reviewers for sensitizing us to this point.

[3] We use the term "affordances" in Gibson's sense such that an artifact possesses the potential for specific interactions given its material properties (Gibson, 1979). As expanded by Leonardi (2011): "Technologies have material properties, but those material properties afford different possibilities for action based on the contexts in which they are used." In this view, affordances can realize features that are both intended or unintended by an artifact's designer, but are always a function of the material properties of an object (digital or physical) even if these properties are not perceived directly (Leonardi 2011 discusses this relationship in detail).

[4] This example is inspired by: Callister and Rethwisch, (2007). *"Materials Science And Engineering: An Introduction," (7th Ed.),* Wiley and Sons, New York.

arrangements into specific forms of data types (e.g., .pptx vs.odp) can afford different functions (such as differences in embedded content or animations) in their given contexts of use. On the other hand, we can also describe how the physical form of an artifact affords or limits its functionality in interacting with or generating digital material. For instance, a security camera which is not equipped with large data storages, requires its recordings to be looped and overwritten, i.e., affording different functionalities as a consequence of its digital material components.

Functions can be seen as enactments of matter and form in contexts. They refer to the realized functionality, i.e., an enacted activity, as opposed to the potential for action as implied by affordances. Therefore, materiality can also be expressed as the relationship between function and matter, i.e., how material is interacted with, manipulated, and produces effects (represented by the arrow "Enactments"). Conceptualizing enactments between matter and function implies a bi-directional relationship. First, there is the interaction between the function and the matter of the artifact itself: e.g., consider how writing with a pencil alters the matter of the pencil's core which, in turn, diminishes its function over time. Second, there are the effects on the material properties of the environment within which the artifact is used: e.g., when an electronic device is damaged if used in hazardous conditions or how the use of a phone as a hammer, while possible, permanently alters its function.

In summary, the spatiotemporal context conditions the interaction with and the perception of any human-made object existing over time and implies a distinction between an artifact itself and an activity afforded by an artifact in context. We draw on this distinction as an analytical device for the review of past literature as it lends a language to describe two facets of physicality that are grounded in work on materiality of technology by attending to the relationship of matter, form, and function.

Step 2: Systematic Literature Search.

Guided by our conceptualization of physicality and its relation to materiality of digital innovation, we engaged in a systematic literature search of empirical work on digital innovation in the information systems as well as broader management field. To conduct the systematic review, we followed the three-step search strategy described by Webster and Watson (2002), involving an initial database search implemented through a search protocol to identify relevant literature and subsequently extending the literature through additional backwards and forward search (see Fig. 3).

For the database search, we focused on the AIS electronic library (AISel) which includes all major IS journals. Additionally, we include the citation database SCOPUS in recognition of the interdisciplinary research stream that is digital innovation (Webster & Watson, 2002). As search terms for the query, we used "PHYSICAL" and "MATERIAL", connected by the OR operator. These terms capture the broad range of papers dealing with physicality while also recognizing the potential ambiguity between physicality and materiality that result from inconsistencies in the conceptual foundations (Leonardi, 2010). In keeping with the main goal of the theoretical review, we appended the term "DIGITAL INNOVATION" via the AND operator to focus the search results on our domain of interest. The search was limited to titles, abstract, and keywords of the respective articles and included only peer-reviewed papers published up to June 2023. Lastly, as per our description above, we narrowed results down to include only studies containing some empirical evidence as part of their work to identify how researchers report, explain, and theorize digital innovation phenomena when having to engage physical artifacts and activities in actuality.

After eliminating duplicates, the above procedures returned 396 publications matching the chosen filter criteria. Due to the broad search approach, it was then necessary to exclude those articles that only made nominal mentions or ambiguous use of search terms (e.g., "the collected material"). The remaining 118 articles were scanned for their substantive engagement with physicality as per our conceptual framing device (see *Step 1*). Through the iterative process of scanning the literature and conceptualizing the phenomenon described above, we excluded papers if they did not substantively address physicality in terms of its attributes when explaining, documenting, or theorizing digital innovation. This left 42 publications for further analysis.

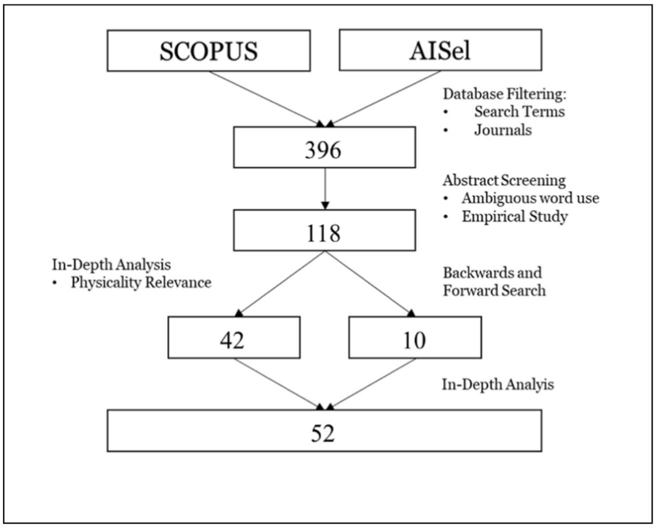


Fig. 3. Visualized Search and Filter Protocol.

Finally, we further expanded the body of work for review through backward and forward search of studies cited in the initial 42 publications. Searching backwards and forwards, while adhering to the same criteria, added another 10 publications.

The above steps yielded a final set of 52 papers that were analyzed in depth. These publications all share a substantive engagement with physicality in relation to digital innovation and the use of empirical evidence in their report. A full list of all studies included in the final set is included in Appendix A. Fig. 3 below provides a visual summary of the literature search and selection process.

Step 3: In-Depth Literature Analysis.

The final set of 52 studies were analyzed in-depth, starting with a close reading by the first author, after which all authors engaged in discussions to converge on (interim) the results of the literature analysis. We developed two coding dimensions to frame the literature by iterating between our conceptual framing device and the in-depth reading of the final set of identified studies: whether studies focused on an artifact or an activity when theorizing as well as the criticality of physicality as a factor in theorizing (see Appendix B for the coding data structure).

There were two stages of our literature analysis. In the first stage of the literature analysis, we initially engaged in descriptive coding through abstraction according to the conceptual framing developed earlier (see 2.1 above). Thus, we coded papers according to their overall topic and focus on physicality. For instance, a paper dealing with *managing time complexities* focused specifically on *temporal dependencies between digital activities and physical bearers* (Bosler et al., 2020). These descriptive codes were abstracted to identify the underlying elements of analysis, such as *synchronization activities*, *new digital product*, or *IT infrastructure*. Subsequently, a second round of abstraction associated the identified elements of analysis with *facets of physicality* guided by our previous conceptual development. The coding dimension differentiated between artifacts and activities as the facet of physicality being focused in the publications. Accordingly, studies that focused on the physicality of artifacts examined if and how the physical attributes and form of physical objects factored in digital innovation. For instance, a study might focus on how physical attributes of an artifact determine the potential value of a digital innovation (Kawakami & Parry, 2015). In contrast, studies that focused on the physicality of activities examined how actors engaged with physical artifacts or how interactions between physical and digital artifacts shaped digital innovation processes and outcomes. An example of the focus on activities is work that investigates the changing relations among stakeholders in diverging physical and digital processes (Svahn et al., 2017). When studies contained elements of both facets of physicality we broke the tie by whichever element – artifact or activity – was most in focus of interest throughout the study to arrive at explanation and theorization of a focal digital innovation.

In the second stage of the analysis, we aimed at explaining the additional variation between publications and their theorization of physicality in relation to digital innovation phenomena. Initially, we engaged in descriptive coding of the impact of physicality, with codes such as *new data sources, new ICT capabilities, constraints of a physical bearer,* or *diverging organizational logics*. However, we realized what differed across studies is the importance given to either a physical artifact or a physical activity in explaining *how* digital innovation unfolded. This insight required us to differentiate studies on digital innovations by the degree to which the treatment of physical artifacts and activities was pivotal to the resulting theorizing of digital innovation in reviewed papers.

The above led us to the formulation of a second coding dimension framing the engagement with physicality in digital innovation research by the extent of the *Criticality for Theorizing.* The treatment of physicality as a critical factor in theorizing the digital innovation differed between studies and tended to range from the context for innovating a physical practice using digital technology to being treated as a driver of digital innovation. Hence, we differentiated studies by whether the materiality (matter, form, function) of a physical artifact or a physical activity was critical to explanations of how digital innovation occurred from those studies where it did not. Specifically, we noted physicality as a *"primary factor"* to indicate studies in which physical artifacts or physical activities were substantive and direct contributors to the specific manifestation of a digital innovation process or outcome as reported in empirical work. In contrast, we coded physicality as a *"secondary factor"* if the physical artifact or activity did not play a critical role in how digital innovation was theorized.

It is important to point out that this step in our analysis of the literature is independent of the phenomenon being reported in a given study. For instance, studies investigating similar or closely related digital innovation phenomena, still diverged in their treatment of physicality. For illustration, consider the papers by Østerlie (2012) as well as Monteiro and Parmiggiani (2019); both study sensor networks intended to capture digital traces of physical phenomena – oil production and marine life environments, respectively. However, the study by Monteiro and Parmiggiani (2019) seeks to understand how an increasing reliance on digital representations of the real-world marine environment alters how social actors think about and engage with phenomena such as fish populations. They find that the perception of the physical practices and reasoning about its consequences are altered when stakeholders engage with the

Criticality of Physicality as Factor in Theorizing		Artifact	Activity
	Primary	**Vessel** of Digital Innovation *17 of 52 papers*	**Nexus** of Digital Innovation *13 of 52 papers*
	Secondary	**Subject** of Digital Innovation *3 of 52 papers*	**Context** of Digital Innovation *19 of 52 papers*
		Facet of Physicality in Focus of Theorizing	

Fig. 4. Four Roles of Physicality Identified from Theoretical Review.

digital traces instead of the physical matter itself. This study is representative of a stream of work that treats physicality of an artifact as secondary to digital innovation and instead points out consequences to artifacts changing social practice. In contrast, Østerlie (2012)'s paper examines how the introduction of digital sensor technology to assess, control, and optimize industrial processes changes the process of oil exploration and production itself. Here, the physical activity is substantially and directly shaped by the digital innovation in focus of this study. Studies like these are thus an example of work giving priority to physicality as a critical part in their theorizing.

Four roles of physicality in digital innovation

Through the in-depth literature analysis outlined above, we frame the engagement with physicality in digital innovation research along two dimensions with two attributes each: the facet of physicality that is the focus of theorizing digital innovation: *artifact or activity* – and the criticality of physicality to theorizing digital innovation: *primary or secondary*. Combining each attribute across both dimensions yields four different roles that physicality can take in the theorization of digital innovation phenomena. We label these roles as follows: 1) Subject, 2) Vessel, 3) Context, and 4) Nexus of Digital Innovation. Below, Fig. 4 shows the results of the systematic literature review synthesized into the four roles. Next, we summarize each role, give examples from the reviewed literature, and reflect on the utility of each role for theorizing digital innovation phenomena.

Physicality as the subject of digital innovation

The first role of physicality we identified relates to physicality as the subject of digital innovation. Studies taking this role mainly focus on physicality of an artifact. However, the physical attributes of an artifact are not treated as critical factors for theorizing how digital innovation occurs. Instead, the physicality is secondary, such that studies tend to treat physical artifacts as the means to the end that is getting at forms and consequences of increasing digitization and digitalization of formerly physical artifacts.

Research with this perspective of physicality implies a subordinate role of physical matter when studying digital innovation. Instead, digital innovation is studied through the functionality of digital artifacts as detached from physical form. Specifically, studies in this space at most contrast physical and digital artifacts to explain the differences in kind between digital and physical material objects and their properties. The material properties of digital artifacts are inferred from functions of digital artifacts which in turn are revealed through digitization – i.e., replacing physical artifacts' form and function by means of representing them digitally.

Existing research ascribing this role to physicality is relatively sparse as any physical artifact is often disregarded upon its digitization. Studies that can be associated with adopting this view involve physical artifacts to demonstrate the differences in kind between a focal digital innovation phenomenon and its non-digital predecessor. Studying digital innovation while treating physicality as the "subject of digital innovation" nevertheless holds the promise to deepen our understanding of how tangible physical objects and the practices they render compare and contrast with digital technology artifacts, yielding insights that contribute to the theoretical foundation of digital innovation in diverse contexts.

As examples, consider the studies by Zhang et al. (2021) and Monteiro and Parmiggiani (2019). Zhang et al. (2021) examine the design of semiconductor chipsets used in a wide range of electronic devices. They emphasize how designers previously relied on their knowledge of the physical attributes of chip components (transistors, plate circuit boards, etc.) to model the input–output relationship that renders chip designs. With the introduction of autonomous tools, the design processes of such chipsets and components were transformed; designers only need to provide incremental sets of constraints for the tools to operate, and are no longer required to understand the underlying physical attributes of the materials that make up a chipset to produce new designs. Yet, in that study, the designers' understanding of the components and the physical attributes of the chips are not used to theorize the digital innovation. Instead, the physical artifact is used as an impetus to highlight how the associated innovation outcome marks a critical departure thanks to the introduction of digital technology.

Another example is a study by Monteiro and Parmiggiani (2019), in which the authors investigate complex physical phenomena in marine environments. They highlight how the use of digital sensors and the analysis of digital traces turns phenomena of physical matter, such as calculating the biomass of fish populations, into phenomena that humans experience only through algorithmic mediation (what they call 'synthetic knowing'). However, the physical attributes of the phenomenon are not critical to their theorization, but instead the physicality is a means to highlight how the understanding of a physical phenomenon is distinct from an algorithmically mediated digital representation of the same phenomenon.

In summary, studies treating the role of physicality as a subject have in common that the physical artifact is not critical to theorizing digital innovation. Instead, physical artifacts are the center of what is being changed through digital innovation. The physical attributes of artifacts are the means to explain how digital innovations occur and what differentiates digital from non-digital innovation processes and/or outcomes.

Physicality as the vessel of digital innovation

A related yet distinct role of physicality on the level of the artifact is what we label *physicality as a vessel of digital innovation*. This role is recognizable in studies that engage with the physicality of an artifact, i.e., the physical attributes of an object's matter, form, and function as a primary factor in theorizing digital innovation. In this body of work, the physical attributes of the artifact in question are a critical component in how digital innovation is studied and understood (e.g., Kawakami & Parry, 2015; Priego & Wareham, 2023; Rayna & West, 2023; Wang, 2022).

When ascribing the role of physicality as a vessel, all three elements of matter, form, and function of physical artifacts are relevant to theorizing. Scholars often build on how the composition of an artifacts' matter, form, and function is changed through digital innovations. However, a clear directionality in the relationship between matter, form, and function can be observed; work subscribing to the role of physicality as a vessel of digital innovation considers how material properties of physical artifacts are key to enabling digital artifacts when physical artifacts are arranged into a form such that they afford novel digital functions. This role thus articulates how physical artifacts moderate the way digital material properties (such as editability, re-programmability, generativity) can play out during innovation.

The role of physicality as a vessel thus underlines the interaction between physical and digital artifacts in our understanding of digital innovation. Existing research associated with this role is prominently concerned with questions of digital innovation in settings that draw on existing physical infrastructures and artifacts that are undergoing digitalization. Accordingly, many organizational-level studies focus on firms exploring existing assets to find opportunities for innovation (Hylving & Schultze, 2020; Priego & Wareham, 2023; Sandberg et al., 2020) or value creation (Bosler et al., 2020; Karagiannis et al., 2022; Kawakami & Parry, 2015) while contained by the properties of physical artifacts.

Consider, for instance, the studies by Wang (2022), Rayna and West (2023), and Priego and Wareham (2023). Wang (2022) explores how physical artifacts can be embedded with digital capabilities to reframe product offerings, particularly when physical artifacts are redesigned to incorporate digital capabilities. Specifically, Wang (2022) examines how physical attributes of a theater factor in shaping the meaning of a physical environment and its artifacts for a "digital theater". The study treats the physical attributes of the theater – such as the location in a building or the interior of the stage room – as critical components in theorizing how digital technologies are deployed to create a new theater experience. The study leverages the role of different physical artifacts to highlight how they afford carrying different digital technologies to deliver varying product propositions.

Rayna and West (2023) consider an existing physical artifact in the case of 3D printing and describe how physical limits of the artifact impacted its potential for digital innovation. Specifically, they demonstrate how – despite the advantages of digital components in 3D printing (i.e., digital design, distribution, re-programmability) – 3D printers make engaging with their physicality inevitable. For instance, additive manufacturing techniques require filament material to be at hand during production and a machine's ability to produce a model from a digital representation accurately is a function of the interaction between printing matter, context of use, and the devices' movable parts. In their assessment, the physical attributes of 3D printing can become bottlenecks for materializing digital innovation, urging researchers to understand the physicality of an artifact as a critical factor in delivering on the potential of digital technology innovations.

Lastly, the study by Priego and Wareham (2023), while primarily focusing on the composition of an artifact (here: a system of devices for synchronization of time for scientific experiments across spatially distributed computing network), addresses the interaction between the physical hardware, its attributes, and the digital innovation processes required to develop the artifact. The authors examine how the physical composition of hardware artifacts affects open innovation practices. Specifically, they observe that an artifact's physical embodiment affords varying innovation activities as a function of the artifact's malleability and plasticity. This highlights how the physicality of the artifact itself is an important factor at the most fundamental level of enabling and constraining digital innovations. They find that the physical attributes of the device shape the interactions that are possible which ultimately makes physicality a determining factor in how innovation processes with and of the device unfolds.

Overall, studies treating physicality as the vessel of digital innovation emphasize the physicality of artifacts as a critical factor in theorizing how digital innovation can be carried out and perceived in the physical world. Typically, this understanding echoes the notion of physical artifacts' form and function acting as a bearer for digital innovation (Faulkner & Runde, 2019). Whether artifacts are passive or active is less important than the fact that physicality is treated as the boundary between the digital technology and the physical world which determines how digital technology is borne, manifested, interacted with, and perceived. In turn, physical artifacts act as interfaces that can be shaped to cross these boundaries and link to novel functions afforded by digital artifacts.

Physicality as the context of digital innovation

Physicality as the context of digital innovation is the third role of physicality we recognized in our review. Studies adopting this role highlight a different facet of physicality – the physicality of an activity – and yet the specifics of how physical objects and their attributes are manipulated or interact in the physical world are not critical factors in how digital innovation is theorized (e.g., Bilgeri et al., 2019; Svahn et al., 2017; Tironi & Valderrama, 2021).

This perspective is most apparent for its limited consideration of physicality in assessing digital innovation. The notion of physical matter is of little interest in this perspective beyond being the setting in which digital innovation occurs. A digital innovation, while enacted varyingly in physical contexts, is determined by the function of a digital artifact to which the material properties of digital or physical artifacts are largely disregarded.

In the view of physicality as the context of digital innovation, researchers tend to treat physical artifacts and activities as a setting to study digital innovation, which often means physicality serves as the explanation of how contextual conditions associated with real world activities influence digital innovations processes and outcomes. Existing research associated with this role is often concerned with understanding how digital innovation can be managed under various contextual conditions – be that social, economic, political etc. However, rather than actively theorizing the contextual influences on digital innovation, studies often treat them as underlying assumptions for how digital innovation occurs. Subsequently the focus lies on the resulting tensions in organizational logics (Moschko et al., 2023; Svahn et al., 2017), social behaviors and policies (Enari & Rangiwai, 2021; Higgins et al., 2017; Tironi & Valderrama, 2021), or new competitive dynamics (Bygstad et al., 2020; Cichosz et al., 2020; Huynh, 2022).

Consider as examples the studies by Tironi and Valderrama (2021), Bilgeri et al. (2019), and Svahn et al. (2017). Tironi and

Valderrama (2021) examine how smart home devices impact the relationship between government authorities and citizens. While the physical sensor network is an important factor in how behavior is monitored and controlled, the focus of the study lies on the policies, behaviors, and perceived privacy incursions of these new technology-mediated interactions. The use of the physical sensor network is a necessary element for the study, but the physical properties are not considered beyond the fact that they allow for efficient and effective monitoring and enforcement of government regulations at a distance. Instead, the paper is focused on the social dynamics that emerge from such a tight entanglement of government and citizens. Accordingly, the physicality of the activity is not critical to theorization as much as it serves as the empirical setting within which the phenomenon of interest occurs.

Bilgeri et al. (2019) similarly treat the interactions, traces, and data streams from physical sensors in various industrial applications – such as the usage rates of printing presses or failure rates in production machinery – as a setting within which they study innovation. Specifically, they find new data streams generated through IoT sensors enable new activities and processes to emerge that were previously inaccessible (e.g., the usage data from printing machines enables new forms of market research for the manufacturer of the printing press). However, the physicality of the activity matters only insofar as sensors trace the movements of objects in space and aggregate information to model processes. Thus, the paper illustrates the emergence of a new opportunity for process innovation on top of and separate from the physical origin of the data.

Finally, the paper by Svahn et al. (2017) reports a case study at Volvo which concerns the physicality of activities surrounding car manufacturing processes. The authors investigate how initiatives at the Swedish car maker seek to integrate hard- and software products in car design practices. They describe the change in interactions between engineers, developers, and managers around the artifact, i.e., a car, due to digital innovation. Specifically, they highlight how interactions centering digital or physical artifacts differ in the organizational processes, capabilities, and incentives required to innovate. But the focus of the study lies not primarily on the changing properties of the car, but instead on how the social interaction during the innovation process is impacted by introducing digital technology into car manufacturing. This means, rather than examining the physicality and eventual changes to an artifact, their study is mainly concerned with the interactions surrounding physical materiality in a given context: e.g., how the use and function of an artifact is a means to an end in the explanation of how the interaction of social actors is affected while innovating.

Overall, studies treating the physicality as context of digital innovation investigate digital innovation that occurs in the physical world, but the physical attributes of artifacts and activities are of little to no criticality for theorizing digital innovation. This is often marked by studies treating physicality as a source of specific boundary conditions for how, why, and what related digital innovation phenomena occur. This perspective can aid in theorizing digital innovation across diverse domains that display difficulties in implementing digital innovation. Such work can focus on the qualifying conditions for digital innovation across different contexts.

Physicality as the nexus of digital innovation

The fourth and last role of physicality we identified is what we call *physicality as the nexus for digital innovation*. Studies ascribing this role to physicality focus on physical activities as a critical factor in theorizing how digital innovation occurs (e.g., Jarvenpaa & Standaert, 2018; Oborn et al., 2021; Østerlie, 2012). This perspective most closely relates to the notion of hybrid phenomena that present an inherent entanglement of physical and digital components, settings, and actors. Under these conditions the relationship between physicality and the materialization of digital innovation is considered bi-directional; matter, form, and function have mutually constitutive relations of arrangements, enactments, and affordances in the emergence of digital innovations.

Physicality as the nexus of digital innovation includes studies in which physical artifacts and activities co-create digital innovations and are factored as a dominant influence in theorizing digital innovation phenomena. Studies taking this view on physicality acknowledge that digital innovation happens in and with the physical world. As such, studies have focused on the mutually constituting dynamics between physical and digital components and activities that drive innovation, such as the constant interplay between situated instances of physical artifacts and environments on the one hand, and continuously generative digital technologies on the other (Jarvenpaa & Standaert, 2018; Lakemond & Holmberg, 2022). While extreme empirical cases like the "Metaverse" are illustrations of this dynamic that are unlikely to achieve more than fad status (Schöbel & Tingelhoff, 2023), studies in this space also focus on the increasing hybrid physical-digital transformation of professional and personal lives, products, and industries (Oborn et al., 2021; Østerlie, 2012; Sundermeier, 2022).

Consider the following examples. First, take the study by Oborn et al. (2021) which investigates the interplay between existing physical practices in the healthcare sector and novel uses of digital technologies. Both the restrictions of physical activity by crisis (i.e., the necessity of social distancing) and the use of digital innovation to communicate at a distance shape novel healthcare practice mediated by digital technology use. The physicality of patient interactions (i.e., a material, highly personal practice tied to places of care and the treatment of patients) is a critical factor in theorizing how and why digital innovation changes practices of medical care. Oborn et al. (2021) document how actors in the healthcare sector, such as doctors and patients, utilized digital technologies to perform their duties of care, despite being physically restricted by social distancing guidelines in their work environment.

Similarly, Østerlie (2012) studies how new processes for oil production result from the close interaction between the physical production activity and digital trace analysis from sensors on the industrial production equipment. The focus of the study lies not merely on understanding the phenomenon through traces but on the actual manifestation of hybrid production processes, thus engaging with the physicality of the activity to generate new permutations of the oil production process.

Lastly, Jarvenpaa and Standaert (2018) demonstrate that altering an existing physical activity yields novel experiences. They study motorsports augmented through digital technologies, e.g., providing additional energy to the engine through optimizing valve operations based on sensor data and signals. Here, digital technology manipulates physical activities in a way that fundamentally alters how the activity occurs, thus revealing unimagined possibilities for digital innovation in the physical world.

Overall, studies engaging with physicality as the Nexus of Digital Innovation focus on the mutually constitutive relationships between physical activities and digital technologies, rendering the physicality of activities an active part of the creation and direction of digital innovation. This perspective aids in reporting the growing share of hybrid phenomena and their constitution of entangled physical-digital materials. Table 1 summarizes the results of the theoretical review.

Research opportunities

Grounded in work on the materiality of digital technology, our theoretical review offers a conceptual lens with which to speak about physicality as it relates to digital innovation. Using this lens, we identified four distinct roles of physicality in empirical research that invite varying perspectives on how matter, form, and function interact to produce digital innovations in the world. As such, each of the roles of physicality that researchers ascribe to will foreground some aspects about physicality and digital innovation while backgrounding others.

To aid future research on digital innovation, in this section, we outline several lines of inquiry that present an opportunity for IS researchers interested in attending to physicality in their work. The roles of physicality offer complementary perspectives, and we illustrate examples of phenomena in each line of inquiry and how work can be advanced through varying constellations of roles of physicality, independently and jointly. The lines of inquiry as well as the combinations of perspectives we outline are mere illustrations of the complementarity of the different roles' physicality can take in digital innovation projects. In line with the scope and aims of our review, we prioritize empirical work emerging along the frontier of research on digital innovation.

Hidden physicality and pervasive digitization

Recent research in the space of digitization of products, processes, organizations and industries (e.g., Hendler & Boer, 2019; Lyytinen, 2022; Zhang et al., 2021) made important inroads but also revealed that physicality still matters when it enables or constraints digitalization, without which there can be no digital innovation. Research on the frontier of ongoing digitalization can be served by at least two complementary perspectives on physicality we suggest here. On the one hand, ascribing the role of *physical artifacts as a subject* of digitalization highlights otherwise unseen constraints to digital innovation. On the other hand, *physicality as a vessel* for digital innovation invites researchers to think about the enabling capacity of physical artifacts and their interaction with digital innovation processes and outcomes.

One promising avenue is reserved for studies that are interested in outcomes of digital innovation. Here researchers have an opportunity to explicitly attend to the role of physicality as *the subject* of digital innovation. Specifically, researchers can increase the depth of their theorizing by including the dependencies between design characteristics of physical artifacts and digital innovation outcomes. Physical artifacts, by virtue of binding materials into a composite object to perform a specific function, define a static link between forms and the functions they embody (Faulkner & Runde, 2019). Studies utilizing the role of *physicality as a subject* imply a shift in the logic of static component-function relationships that result from digitizing physical artifacts (cf. Baskerville et al., 2020). Incorporating these ideas into research on digitalization opens opportunities to evaluate the interaction between physical artifacts and digital innovation outcomes.

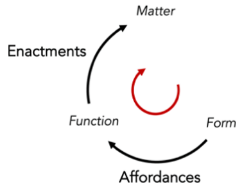
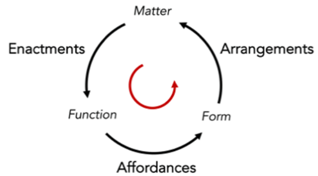
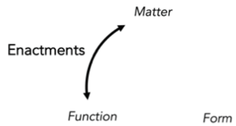
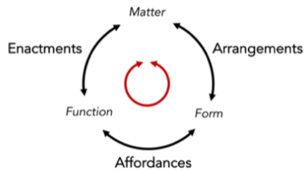
For instance, dynamics in digital product innovation such as "smart consumer devices" (Lee et al., 2020) or the "(industrial) internet of things" (Bilgeri et al., 2019) will surely find ways to replace and amend physical with digital artifacts, yet various cases will not be able to be digitized fully, leaving physical artifacts as remnants. Wherever physical artifacts remain, physically-centered and digitally-centered innovation logics will have to be aligned (e.g., Hendler & Boer, 2019; Lyytinen, 2022). Critical to such alignments will be an understanding of what and how physical artifacts, wholly or in parts – can be represented digitally and thus abstracted – and indeed when this is not possible (e.g., Lee & Berente, 2012). Here, the frontier of what is achievable through digitalization, and how, is served by researchers considering the role of *physicality as a subject* as this can help explain the creation of innovative outcomes (Yoo & Euchner, 2020).

Another opportunity for IS research is to uncover previously hidden physicality of the digital infrastructure fueling digital innovations (e.g., Tilson et al., 2010). Consider for example how cloud-based digital platforms decouple their service offering from physical infrastructures (Benlian et al., 2018) and are often seen as "pure" digital services (Yoo & Euchner, 2020). Nevertheless, these digital services rely on the unseen physical infrastructures and are shaped by them. For instance, streaming services push popular content to physical local servers to minimize data streams and loading times and steer demand by tailoring their recommendations according to which files are accessible locally (Sermpezis et al., 2018). Uncovering the role of otherwise hidden physicality such as this can be provided by the role of *physicality as a subject*. Attention paid to this, in turn, advances research on the organizational activities drawing from underlying digital infrastructures (cf. Henfridsson & Bygstad, 2013; Rodon Modol & Eaton, 2021) thus asking *"what are the limits of digitization and how do they shape the deployment of digital services"?*

In addition, the uncovering of 'hidden' physicality as described above can be complemented by work with the role of *physicality as a vessel* for digital innovation, providing a perspective that highlights the interaction of physical artifact designs with digital innovation processes (Lyytinen et al., 2016; Nambisan, 2013; Nylén & Holmström, 2015).

Here, a concrete opportunity for research lies in recognizing that physical artifacts invite cascades of digital innovations in areas that were formerly sparsely digitalized (Boland et al., 2007; Bosler et al., 2020; Hylving & Schultze, 2020). The opportunity for research lies in deepening our understanding of how and which parts of physical artifacts can act as entry points to leverage digital innovations (see e.g., Boland et al., 2007). Emergent work in this space has convincingly demonstrated how the existence of physical artifacts invites digital innovations through activities such as collecting and analyzing data from physical objects (Avital et al., 2023;

Table 1
Results of Theoretical Review.

Role of Physicality	Summary Description	Utility for Theorizing	Treatment of Physicality		Representative References
Physicality as Subject of Digital Innovation	Physical artifacts are the means to the end that is describing novel digital functions that no longer rely on physical artifacts. <u>Physicality viewed as:</u> Contrast, substitute, subordinate to digital artifacts.	Explicating the unique attributes of digital artifacts in digital innovation.	Digital material properties of artifacts are inferred from functions of digital artifacts which in turn are revealed through digitization i.e., representing physical artifacts digitally.		Hendler & Boer, 2019; Monteiro & Parmiggiani, 2019; Zhang et al., 2021
Physicality as Vessel of Digital Innovation	Physical artifacts are a critical component to shaping specific instances of digital innovation. <u>Physicality viewed as:</u> Interface, resource, components that interact with digital artifacts.	Linking physical attributes of an artifact to novel use of digital technologies.	Physical material properties of artifacts enable digital artifacts' function and form which, in turn, determine how digital material features (e.g., editability, reprogrammability, etc.) can be enacted.		Bosler et al., 2020; Kawakami and Parry, 2015; Lee and Berente, 2012; Priego and Wareham, 2023; Rayna and West, 2023; Wang, 2022; Hylving and Schultze, 2020
Physicality as Context of Digital Innovation	Studies focus on digital innovation occurring in environments involving physical artifacts and activities. <u>Physicality viewed as:</u> Constraint, boundary condition, setting for digital artifact use.	Qualifying digital innovation in light of constraints and contextual conditions that are unique to a respective domain.	Digital innovation is enacted within the boundaries set by physicality. Arrangements of matter into form as well as the affordances of physical artifacts are largely inconsequential.		Bilgeri et al., 2019; Boland et al., 2007; Bygstad et al., 2020; Gal et al., 2022; Svahn et al., 2017; Tironi and Valderrama, 2021
Physicality as the Nexus of Digital Innovation	Studies focus on physical activity and its interaction with digital technologies. <u>Physicality viewed as:</u> Fusion, enabler, hybrids of physical-digital artifacts used to innovate.	Fusing of how, why, and where digital innovation occurs when it involves the interaction of physical and digital artifacts and activities.	Matter, form, and function have mutually constitutive relations of arrangements, enactments, and affordances jointly shaping the generation of digital innovations		Jarvenpaa and Standaert, 2018; Lakemond and Holmberg, 2022; Oborn et al., 2021; Saarikko, 2016; Sundermeier, 2022; Østerlie, 2012

Monteiro & Parmiggiani, 2019). The role of *physicality as a vessel* for digital innovation, however, can help explain variations in the unfolding of digitalization. Such work promises to reveal how tangible features of everyday objects, industrial equipment, or specific purpose devices enhance or hinder digital innovation initiatives as well as their adoption, use, and success.

Specifically, the digital innovation literature articulates an interest in these phenomena as "leverage points" (Goebeler et al., 2021; Lyytinen, 2022) for subsequent digital innovation activities following the reciprocal and mutually reinforcing dynamics of digitizing (encoding information digitally) and digitalizing (deploying digital artifacts). Consider how actors in the Formula E motorsports series leverage digital sensors and controls in cars for further innovations, such as a "Ghost Racing" against the digitalized race performance of a professional racer, or "Attack Mode" as a novel racing feature that unlocks additional energy for the driver upon activation of specific sensors (Goebeler et al., 2021; Jarvenpaa & Standaert, 2018). Attending to *physicality as a vessel* and its effect on the generation of digital innovation can potentially reinvigorate research into digital innovation of physical objects as a function of the manipulation of their digital representation counterparts (e.g., Boland et al., 2007; Kyriakou et al., 2017). In this view, digital innovations involving physical artifacts are always both the result of and the basis for further digital innovation activities. This virtuous circle needs to start somewhere and the view of *physicality as a vessel* assists researchers in pinpointing the emergence of digital innovations in the digitalization of physical artifacts' design and architecture (e.g., Hylving & Schultze, 2020).

Hybrid physical-digital innovation

Another line of inquiry that stands to benefit from various perspectives on physicality are hybrid physical-digital innovation phenomena. This includes but is not limited to artifacts that are mutually constituted by physical and digital components and their functionality. Such work assumes that a growing class of digital product innovations never had an "industrial-regime" counterpart (Lyytinen, 2022) of a physical product which is rendered "smart" by the inclusion of digital computing capability. Instead, hybrid physical-digital innovation phenomena are argued to challenge our understanding when physical as well as digital components and artifacts are equally required to create new functionality in a product or process. Understanding how digital innovation occurs under this hybridity and how it can be managed presents a promising frontier for researchers with an interest in physicality.

A prominent example in the digital technology innovation literature are products innovations such as 3D printers (e.g., Beltagui et al., 2020). These artifacts – and many like them – are illustrative of the changes in practices, outcomes, and dynamics of digital innovation when this involves artifacts that cannot be reduced to either digital or physical parts.

To that end, studies leveraging the role of *physicality as a vessel* can deliver a perspective on hybrid physical-digital innovations that foregrounds interaction between digital and physical artifacts to understand innovation processes. The promise of research in this line of inquiry is that the relationship between physical and digital artifacts, which is often seen as unidirectional, can also include synergistic facets.

The literature on hybrid-physical digital innovation phenomena is young but growing (Wang, 2021; Lorenz et al., 2024). Instead of focusing only on the unidirectional embedding of a physical artifact with a digital artifact, studies of hybrid physical-digital innovation foreground the bidirectional binding of material across layered modular architectures (Hylving & Schultze, 2020; Yoo et al., 2010). For instance, the modularity of hardware may facilitate more open use and innovation of digital artifacts (Priego & Wareham, 2023), the physical properties of a 3D-printer may shape development of novel software functionality (Rayna & West, 2023), and the perception and control of physical senses may allow for more deliberate choices in service design in order to create vivid experiences in augmented and virtual worlds (Lorenz et al., 2024). By uncovering how hybrid physical-digital innovations affect recombination, organization, or development of novel products and services, research with this role will help generate explanations of how the transition from separate to joint innovation dynamics occurs when artifacts are both physical and digital by default.

Hybridity does not only involve changes to product or process innovation. Hybrid physical-digital innovation also give rise to ecosystemic dynamics that digital innovation researchers will seek to understand. For researchers interested in *physicality as the nexus* of digital innovation, this finding opens vistas for research on transformation of the roles, relationships, and value creation mechanisms within interconnected networks of physical and digital artifacts and activities (e.g., Lehmann et al., 2022; Wang et al., 2022). In particular, investigating the interfaces between physical and digital artifacts can contribute to the understanding of complex innovation systems conditional on attending to the attributes of physical artifacts and desired activities performed with them (see e.g., Gupta et al., 2023). Research in this area can reveal which innovations are the basis for and the driver of hybrid physical-digital environments providing input in various modality (e.g., VR, AR, voice, haptic, spatial computing).

Lastly, hybrid physical-digital innovation conceivably affects the type of organizations that produce such innovations. This will require that researchers develop cross-domain insights which in turn can be served by taking on the role of *physicality as a context* for digital innovation. The literature on digital innovation draws from a rich tradition of investigating how various organizational settings yield different results when implementing digital innovation (e.g., Bengtsson & Agerfalk, 2011; Wastell, 2006). Including physicality in future examinations can advance this work when attending to contexts marked by differences in their physicality. In this, one specific opportunity revolves around the idea that physical artifacts are external enablers of digital innovation, shaping the emergence and direction of the actors creating digital innovations (Lyytinen, 2022; von Briel et al., 2018b). An external enabler acts on the individual, organizational, or supra-organizational levels of analysis (von Briel et al., 2018b) and would describe the influence hybrid physical-digital artifacts have on the organization of novel forms of economic activity. For instance, much can still be learned about how hybrid physical-digital artifacts shape pace, timing, and impact of innovative changes (e.g., Lyytinen et al., 2016), or how such changes relate to firm-level outcomes of interest for researchers on the intersection of digital innovation and management in new technology ventures (Nambisan et al., 2017; von Briel et al., 2018b). In that vein, the role of *physicality as a context* of digital provides the foundation for a careful assessments of which and why specific features of digital technology enable or constrain innovators (e.g., von Briel et al., 2018a).

Physicality and organizing digital innovation

In this last line of inquiry, we cover research opportunities that accentuate physical artifacts and activities as the centerpiece of organizing human activity. This allows us to broaden our conception of organizing digital innovation with respect to different roles of physicality and its consequences for thinking about boundaries of work and organization as well as consequences of digital innovation in markets and industries. Several views on physicality are well suited to advance work in this space.

First, *physicality as a vessel* for digital innovation invites thinking about the bindings between tasks, locations, actors, tools, and assets (cf. Baskerville et al. 2020) that determine much of modern economic activity. Since digital innovation requires the integration of digital and physical design processes, research into the organizational practice of innovation will have to account for how digital technology use fuels the transfiguration of work and it boundaries (e.g., Henfridsson et al., 2018; Lyytinen et al., 2023; Nylén & Holmström, 2015). Applying the lens of *physicality as a vessel* will allow questioning how distributed innovation proceeds as well as what organizational designs lend themselves to such processes.

An example of how physicality can become relevant in cases of distributed digital innovation can be found among the recent *CrowdStrike* outage. While IT teams and service providers were typically able to remotely troubleshoot issues even across distributed locations and actors, the outage required many organizations to manually access thousands of physical devices distributed across their worksites. While a digital fix was released within 78 min, it took days for IT administrators to access all affected devices (Lyons, 2024; microsoft.com, 2024). Albeit an extreme case, this example shows how an organization's effectiveness to manage distributed digital systems hinges on its ability to address the physicality of the devices used in deployment of the system. In the case of *CrowdStrike,* American Airlines was able to organize response teams and recover almost completely within 24 h, while Delta Airlines took more than five days (Ashare, 2024).

The role of *physicality as a vessel* is well suited to incorporate thinking about the interaction of digital and physical resources and thus add to the burgeoning work on the resource-level of analysis in digital innovation (Henfridsson et al., 2018; von Briel et al., 2018a). This perspective prioritizes a view on digital innovation as managing resources through recombination-in-use (e.g., Henfridsson et al., 2018) and can be extended to studies favoring recombination-in-design (e.g., Kyriakou et al. 2017). Either way, researchers interested in organizations that innovate by combining digital and physical resources, *physicality as a vessel* can lend focus as it provides a language to describe the varying logics of design and management that digital and physical artifacts are subject to.

The role of *physicality as the nexus* for digital innovation promises to advance another interesting avenue related to the organization of digital innovative labor (Lee & Berente, 2012). Digital innovation is often assumed to distribute innovation agency as digitally encoded information can be manipulated by human and non-human actors and from various sources due to digital artifacts' editability, interoperability, and accessibility (Yoo et al., 2012). Often summarized as "digital first" (Baskerville et al., 2020), the view suggests that digital technologies lead to the emergence of distributed innovation processes, where the boundaries of organizations become more and more permeable, such that innovation activities span across different entities and sectors. However, as distributed work and permeable innovation activities become more common, researchers must also consider the different configurations of work that emerge as a result (Robey et al., 2003). For instance, work will involve combinatorial input to digital innovations that are spatially and temporally distributed across a wide range of actors –- freelancers, contractors, and other partners (Jimenez et al., 2017) across physical places and assets. This plurality of factors can be well served when attending to *physicality as a nexus of digital innovation.*

One phenomenon expected to bring out these dynamics are "digital twins"; deploying and managing virtual replicas of physical products and processes will require the manipulation of resources across digital and physical design hierarchies including organizational division of work and specialization within the same organization (Lyytinen et al., 2023). Clearly, organizing digital innovation involving physical artifacts will shape the type of organization that can engage in such work. Mostly, it implies a dual capability to produce both digital and physical artifacts (cf. von Briel et al., 2018b) and integrating physical artifacts and activities necessitates adapting innovation processes. This is a matter of course for digital innovation researchers, yet, the decoupling of organizational innovation processes can only go so far (e.g., Svahn et al., 2017): As a consequence, this will require researchers to understand how, when, and if to alter the dependencies between digital and physical material (places, things, tasks, actors, etc.), and their corresponding activities (Lyytinen et al., 2016; Sandberg et al., 2020).

Consider an example from the (industrial) Internet of Things: to conduct predictive maintenance or demand forecasting on physical assets, it is necessary to know where and when a machine is used, how the machine operates and was supplied, where and how data is collected and generated. Organizations engaging in these practices need to understand the entirety of the situational context, including both the digital software and the physical asset, as well as the interaction between involved actors and the relation to other processes (Avital et al., 2023). Research in these questions stands to gain scope and focus by describing how and which activities are carried out in organizations driving digital innovations by attending to *physicality as the nexus* of digital innovation.

Finally, a salient opportunity in the space of organizing and digital innovation is to extend the literature on scaling of digital ventures by opening up the role of physicality and attending to its role as *context for digital innovation.* Therein, researchers should consider the interaction between organizations that develop digital innovations and the environment in which they are deployed. Consider how much of the recent work on digital platform ventures investigates the limits of network effects and associated market outcomes as well as necessary organizational set up to operate digital platform organizations. Here, the leanness of digital business affords growth through rapid scaling and pivots in product development by utilizing and contributing to digital infrastructures (Henfridsson & Bygstad, 2013; Huang et al., 2017; Huang et al., 2022).

Such work on scaling digital innovations can be informed by the role of *physicality as a context* which would expose that scaling is constrained by the physicality of the setting in which it unfolds. Digital ventures scale rapidly thanks to digital technology (e.g., Huang et al., 2017, 2022). New business models are often resting on increasing returns to scale through network effects and feedback loops. But digital ventures do not operate in a vacuum. In cases where these digital innovations involve physical artifacts, they impose the dynamics of a digital world on the social and economic dynamics they address. More and more work engages with the opportunities and challenges stemming from the externalities when physical activities are affected by new ventures and the pace with which ventures innovate (Garud et al., 2022; Recker et al., 2024). For instance, network effects can wreak havoc when digital services meet the finite capacities of physical artifacts, such as utilization of housing, cars, or restaurants, as well as travel time between locations, preparations of meals, resource supply, etc. Attending to *physicality as the context* would allow researchers to investigate how the mismatch between digital and physical activities produces organizational and market level outcomes that defy the predictions of boundaryless growth through digital business. Our conceptualization of physicality aids in these efforts by lending a language to frame the interaction of physical and digital activities at varying levels of abstraction. Henfridsson (2020), for instance, asks *"how and why does the nature of digital infrastructure influence the scaling process"*, by the same token, one can ask *"how and why does physicality shape the scaling of digital innovation?"*

The lines of inquiry we suggest above are mere suggestions informed by the interests of the author team. Table 2 summarizes several opportunities as well as illustrative examples of phenomena that can be investigated when subscribing to one or more of the roles of physicality in digital innovation – regardless of whether or not researchers wish to engage in any of the lines of inquiry we highlighted above.

Discussion

A growing body of work engages the complexities of digital innovation involving both digital and physical artifacts (e.g., Hylving and Schultze, 2020; Lehmann et al., 2022; Priego and Wareham, 2023; Svahn et al., 2017; von Briel et al., 2018a; Wang et al., 2022). Yet how physicality relates to digital innovation, how physicality is understood, and how physicality is treated in theorizing digital innovation differs widely. The digital innovation literature thus finds itself at a crossroads, since to advance the work on digital innovation requires a consistent theoretical foundation to explain innovation in a world that is not just digital. Indeed, attending to physicality in digital innovation is challenging as implicit ontological and epistemological assumptions have to be made explicit using the ambiguous language available to describe anything physical in our field. Just consider the ambiguity around the term "material" as a descriptor for many things ranging from matter as in an object to mattering as in importance (see Leonardi, 2010). As we have demonstrated in this review, researchers do not yet share a language to describe physicality or to conceptualize its role in digital technology enabled innovation.

Against this backdrop, we conducted a theoretical review of the empirical digital innovation literature to consolidate the roles physicality can play in explanations of digital innovation. Our review makes three important contributions.

The first contribution is that it offers a language with which to describe digital innovation in a physical world. More specifically, we draw from first principal attributes of space and time to describe objects that possess mass, volume, and location as well as their manipulation over time, that is, the spatiotemporal context of any object (cf. Yoo, 2010). These basic principles provide the minimal necessary requirements to describe any object in the world without having to subscribe to any philosophical assumption. Such a view combines the spatiotemporal context of objects with ideas from materiality (Kallinikos, 2012; Leonardi, 2012) which enables researchers to distinguish between the physical constitution of objects and the context of their use. This language thus serves as a foundation for statements about when, which, and how physical attributes of artifacts or activities shape digital innovation as a

Table 2
Summary of Research Opportunities.

Role of Physicality	Research Opportunities	Illustrative Phenomena
as a Subject	• The limits and constraints of digitization and digitalization in the physical world The features and properties of physical artifacts that explain variation in digital innovation outcomes	• (industrial) internet of things (I)IoT Product design and development Cloud computing services Digital infrastructure
as a Vessel	• The leverage points for digital innovation across a physical artifact architecture The interaction of digital and physical material in designing, deploying, and managing hybrid physical-digital innovations The dependencies between digital and physical material, their corresponding activities and distributed organizational designs	• Digital infrastructure Product design and development Recombination (−in-use/−in-design) Digital services and experiences Hybrid "smart" artifacts (e.g., 3D printers, connected cars, etc.)
as a Context	• The specific features of digital technologies that enable and/or constrain innovators The effect of physicality of digital innovation on organizational-level outcomes (scaling, success, survivial, etc.)	• Digital ventures External enablers Discontinous technological change ('disruption')
as a Nexus	• The initiation, design, and use of interfaces between physical and digital artifacts in complex digital innovation systems The emergence and evolution of hybrid physical-digital innovation ecosystems	• Interfaces/interfacing New forms of work Organizational designs Innovation processes Digital Platforms and Ecosystems

phenomenon that *relates to and imposes on physical form, matter, and function.*

Here our review distinguishes physicality from materiality, allowing researchers to communicate nuanced views on how digital innovation is realized as well as how it is affected by and in turn affects its spatiotemporal context. Work in other IS sub disciplines – such as human computer interaction (HCI) – have long established that material properties of both digital and physical artifacts affect the design and use of digital technology (e.g., Giaccardi & Karana, 2015). Thus far, this has not been done consistently in the digital innovation literature. To that end, using a concise language of physicality like the one we have developed here is valuable as it facilitates advancing the literature by providing the least common denominator. At the same time, the vocabulary helps researchers justify when the physicality of the digital innovations requires recognition in their work and when it does not. This is useful for anyone engaging with physicality to advance the understanding of digital innovation (e.g., Hylving & Schultze, 2020; Lehmann et al., 2022; Wang et al., 2022; Lorenz et al., 2024).

The second contribution of this review is the conceptualization of four roles of physicality when theorizing digital innovation. These roles highlight the differences in how physicality relates to digital innovation and offer complementary perspectives, each with their own utility for theorizing. The identified roles offer researchers a way to select an appropriate perspective on physicality given their question of interest and a means of articulating their positioning. The conceptual lens we propose is scale-free (i.e., applicable across levels of analysis), is parsimonious (i.e., focuses on the relationships between matter, form, and function of any artifact), and makes few epistemological assumptions. This offers the possibility to develop rich views on the properties of technology artifacts, their integration and use, as well as organizational dynamics.

Finally, our last contribution lies in the research agenda we have laid out for future work on digitalization guided by our conceptualization of physicality. In each of the three lines of inquiry we have identified – namely hidden physicality and pervasive digitalization, hybrid physical-digital innovation, and physicality and organizing digital innovation – we provided some initial ideas and specific examples on how researchers can tackle different problems by taking different perspectives of physicality's role in digital innovation. By extension, it is thinkable to use the roles for two simultaneous objectives: revisit extant studies on digital innovation adoption and implementation – through approaches such as a theoretical review (Leidner, 2018; Pare et al., 2015) or a *meta*-analysis (King & He, 2005); and engage in contextualized theorization (Hong et al., 2014; Johns, 2017) to highlight how multiple roles of physicality help unearth varying insights from already documented phenomena. We also invite researchers to study one and the same digital innovation phenomenon (see e.g. Table 2) from multiple perspectives, thereby advancing literature streams ranging from digital infrastructures (Tilson et al. 2010), over ventures (Recker et al., 2024), scaling (Huang et al., 2017; Huang et al., 2022), recombination (Henfridsson et al. 2018), interfaces (Lipp et al., 2022), as well as product/service design (Wang, 2022; Lorenz et al., 2024).

Conclusion

In this paper, we suggest a conceptualization of physicality that can serve as a point of departure for anyone interested in describing digital innovations that interact with and are part of the physical world. Using language grounded in work on the materiality of technology allowed us to conceptualize four different roles of physicality which provide a foundation from which to engage with physicality in digital innovation and do so consistently. We hope this theoretical review will initiate a discussion of physicality in digital innovation research by underscoring that digital innovation does not occur in a vacuum. To that end, we aim to provide a theoretical foundation on which digital innovation scholars can build and take seriously the role of physicality in their work.

CRediT authorship contribution statement

Lucas Goebeler: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Philipp Hukal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Xiao Xiao:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1
Categorized literature overview.

ID	Authors	Title	Year	Journal	Focused Facet of Physicality	Criticality for Theorizing	Role of Physicality in Digital Innovation
1	Hendler, S., & Boer, H.	Digital-physical product development: a qualitative analysis	2019	European Journal of Innovation Management	Artifact	Secondary	Subject
2	Monteiro, E., & Parmiggiani, E.	Synthetic Knowing: The Politics of the Internet of Things	2019	MIS Quarterly	Artifact	Secondary	Subject
3	Zhang, Z., Yoo, Y., Lyytinen, K., & Lindberg, A.	The Unknowability of Autonomous Tools and the Liminal Experience of Their Use	2021	Information Systems Research	Artifact	Secondary	Subject
4	Baier, M., Berger, S., Kreuzer, T., Oberländer, A., & Räglinger, M	What Makes Digital Technology? A Categorization Based on Purpose	2023	Communications of the Association for Information Systems	Artifact	Primary	Vessel
5	Bosler, M., Burr, W., & Ihring, L.	Digital Innovation in Incumbent Firms: An Exploratory Analysis of Value Creation	2020	International Journal of Innovation and Technology Management	Artifact	Primary	Vessel
6	Brandt, T., Feuerriegel, S., & Neumann, D.	Modeling Interferences in Information Systems Design for Cyberphysical Systems: Insights from a Smart Grid Application	2017	European Journal of Information Systems	Artifact	Primary	Vessel
7	Hauser, M., Günther, S., Flath, C., & Thiesse, F.	Towards Digital Transformation in Fashion Retailing: A Design-Oriented IS Research Study of Automated Checkout Systems	2019	Business & Information Systems Engineering	Artifact	Primary	Vessel
8	Hylving, L., & Schultze, U.	Accomplishing the layered modular architecture in digital innovation: The case of the car's driver information module	2020	The Journal of Strategic Information Systems	Artifact	Primary	Vessel
9	Karagiannis, D., Buchmann, R., & Utz, W.	The OMiLAB Digital Innovation environment: Agile conceptual models to bridge business value with Digital and Physical Twins for Product-Service Systems development	2022	Computers in Industry	Artifact	Primary	Vessel
10	Kawakami, T., & Parry, M.	The Adoption of Electronic Innovations with Indirect Network Externalities that Compete with Standalone Physical Products	2015	Creativity and Innovation Management	Artifact	Primary	Vessel
11	Lakhal, O., Chettibi, T., Belarouci, A., Dherbomez, G., & Merzouki, R.	Robotized Additive Manufacturing of Funicular Architectural Geometries Based on Building Materials	2020	IEEE/ASME Transactions on Mechatronics	Artifact	Primary	Vessel
12	Lee, J., & Berente, N.	Digital Innovation and the Division of Innovative Labour: Digital Controls in the Automotive Industry	2012	Organization Science	Artifact	Primary	Vessel
13	Nyambane, R.	The future of the printed book in the era of technological advancement: an imperative for digital innovation and engagement	2020	Journal of Information, Communication and Ethics in Society	Artifact	Primary	Vessel
14	Priego, P., & Wareham, J.	From Bits to Atoms: White Rabbit at CERN	2023	MIS Quarterly	Artifact	Primary	Vessel
15	Rayna, T., & West, J.	Where digital meets physical innovation: Reverse salients	2023	Journal of Product Innovation Management	Artifact	Primary	Vessel

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Table A1 (*continued*)

ID	Authors	Title	Year	Journal	Focused Facet of Physicality	Criticality for Theorizing	Role of Physicality in Digital Innovation
		and the unrealized dreams of 3D printing					
16	Sandberg, J., Holmström, J., & Lyytinen, K.	Digitization and phase transitions in platform organizing logics: Evidence from the process automation industry	2020	MIS Quarterly	Artifact	Primary	Vessel
17	Sharara, S., & Radia, S.	Quick Response (QR) codes for patient information delivery: A digital innovation during the coronavirus pandemic	2022	Journal of Orthodontics	Artifact	Primary	Vessel
18	Wang, G.	Digital reframing: The design thinking of redesigning traditional products into innovative digital products	2022	Journal of Product Innovation Management	Artifact	Primary	Vessel
19	Wang, R., & Miller, C.	Complementors' engagement in an ecosystem: A study of publishers' e-book offerings on Amazon Kindle	2020	Strategic Management Journal	Artifact	Primary	Vessel
20	Bilgeri, D., Fleisch, E., Gebauer, H., & Wortmann, F.	Driving Process Innovation with IoT Field Data	2019	MIS Quarterly Executive	Activity	Secondary	Context
21	Boland, R., Lyytinen, K., & Yoo, Y.	Wakes of Innovation in Project Networks: The Case of Digital 3-D Representations in Architecture, Engineering, and Construction	2007	Organization Science	Activity	Secondary	Context
22	Bosworth, G., Ardley, B., & Gerlach, S.	Innovation in agricultural and county shows: conceptualising the e-eventscape	2021	International Journal of Event and Festival Management	Activity	Secondary	Context
23	Bygstad, B., Iden, J., & Ulfsten, A.	Digital Business Strategies for Incumbent Firms. How a Scandinavian hotel chain competes with the internet giants	2020	Scandinavian Journal of Information Systems	Activity	Secondary	Context
24	Cichosz, M., Wallenburg, C., & Knemeyer, A.	Digital transformation at logistics service providers: barriers, success factors and leading practices	2020	International Journal of Logistics Management	Activity	Secondary	Context
25	Cranefield, J., & Pries-Heje, J.	Boundary Management Strategies for Leading Digital Transformation in Smart Cities	2023	MIS Quarterly Executive	Activity	Secondary	Context
26	Enari, D., & Rangiwai, B.	Digital innovation and funeral practices: Māori and Samoan perspectives during the COVID-19 pandemic	2021	AlterNative	Activity	Secondary	Context
27	Faik, I., Thompson, M., & Walsham, G.	Designing for ICT-Enabled Openness in Bureaucratic Organizations: Problematizing, Shifting, and Augmenting Boundary Work	2019	Journal of the Association for Information Systems	Activity	Secondary	Context
28	Gal, U., Berente, N., & Chasin, F.	Technology Lifecycles and Digital Technologies: Patterns of Discourse across Levels of Materiality	2022	Journal of the Association for Information Systems	Activity	Secondary	Context
29	Hanelt, A., Firk, S., Hildebrandt, B., & Kolbe, L.	Digital M&A, digital innovation, and firm performance: an empirical investigation	2021	European Journal of Information Systems	Activity	Secondary	Context
30	Higgins, V., Bryant, M., Howell, A., & Battersby, J.	Ordering adoption: Materiality, knowledge, and farmer engagement with precision agriculture technologies	2017	Journal of Rural Studies	Activity	Secondary	Context
31	Huynh, P.	Enabling circular business models in the fashion industry: the role of digital innovation	2022	International Journal of Productivity and Performance Management	Activity	Secondary	Context

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Table A1 (*continued*)

ID	Authors	Title	Year	Journal	Focused Facet of Physicality	Criticality for Theorizing	Role of Physicality in Digital Innovation
32	Hylving, L., Henfridsson, O., & Selander, L.	The Role of Dominant Design in a Product Developing Firm's Digital Innovation	2012	Journal of Information Technology Theory and Application	Activity	Secondary	Context
33	Kyriakou, H., Nickerson, J. V., & Sabnis, G.	Knowledge Reuse for Customization: Metamodels in an Open Design Community for 3D Printing,	2017	MIS Quarterly	Activity	Secondary	Context
34	Marion, T. J., & Fixson, S. K.	The Transformation of the Innovation Process: How Digital Tools are Changing Work, Collaboration, and Organizations in New Product Development	2021	Journal of Product Innovation Management	Activity	Secondary	Context
35	Moschko, L., Blazevic, V., & Piller, F.	Paradoxes of implementing digital manufacturing systems: A longitudinal study of digital innovation projects for disruptive change	2023	Journal of Product Innovation Management	Activity	Secondary	Context
36	Ramaswamy, V., & Ozcan, K.	Offerings as Digitalized Interactive Platforms: A Conceptual Framework and Implications	2018	Journal of Marketing	Activity	Secondary	Context
37	Svahn, F., Mathiassen, L., & Lindgren, R.	Embracing Digital Innovationin Incumbent Firms: How Volvo Cars managed Competing Concerns	2017	MIS Quarterly	Activity	Secondary	Context
38	Tironi, M., & Valderrama, M.	Experimenting with the Social Life of Homes: Sensor Governmentality and Its Frictions	2021	Science as Culture	Activity	Secondary	Context
39	Ayre, M., Mc Collum, V., Waters, W., Samson, P., Curro, A., Nettle, R., Paschen, J., King, B., & Reichelt, N.	Supporting and practising digital innovation with advisers in smart farming	2019	NJAS – Wageningen Journal of Life Sciences	Activity	Primary	Nexus
40	Cook, J., & Mirashrafi, S.	Point Cloud to Sound Cloud Digital Innovation and Historic Sound at Linlithgow Palace	2022	Magazen	Activity	Primary	Nexus
41	Jarvenpaa, S., & Standaert, W.	Digital Probes as Opening Possibilities of Generativity	2018	Journal of the Association for Information Systems	Activity	Primary	Nexus
42	Lakemond, N., & Holmberg, G.	The quest for combined generativity and criticality in digital-physical complex systems	2022	Journal of Engineering and Technology Management	Activity	Primary	Nexus
43	Lee, J., Hsu, C., & Silva, L.	What lies beneath: Unraveling the generative mechanisms of smart technology and service design	2020	Journal of the Association for Information Systems	Activity	Primary	Nexus
44	Lehmann, J., Recker, J., Yoo, Y., & Rosenkranz, C.	Designing Digital Market Offerings: How Digital Ventures Navigate the Tension Between Generative Digital Technology and the Current Environment	2022	MIS Quarterly	Activity	Primary	Nexus
45	Oborn, E., Pilosof, N. P., Hinings, B., & Zimlichman, E.	Institutional logics and innovation in times of crisis: Telemedicine as digital 'PPE'	2021	Information and Organization	Activity	Primary	Nexus
46	Østerlie, T.	Co-materialization: Digital innovation dynamics in the offshore petroleum industry	2012	In: Bhattacherjee, A., Fitzgerald, B. (eds) Shaping the Future of ICT Research. Methods and Approaches. IFIP Advances in Information and Communication Technology	Activity	Primary	Nexus
47	Saarikko, T.	Platform Provider by Accident – A Case Study of Digital Platform Coring	2016	Business & Information Systems Engineering	Activity	Primary	Nexus

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Table A1 (*continued*)

ID	Authors	Title	Year	Journal	Focused Facet of Physicality	Criticality for Theorizing	Role of Physicality in Digital Innovation
48	Schöbel, S., & Tingelhoff, F.	Overcoming Challenges to Enable the Potential of Metaverse Platforms: A Qualitative Approach to Understand Value Creation	2023	AIS Transactions on Human-Computer Interaction	Activity	Primary	Nexus
49	Sundermeier, J.	Lessons for and from Digital Workplace Transformation in Times of Crisis	2022	MIS Quarterly Executive	Activity	Primary	Nexus
50	Wang, Y., & Coe, N.	Platform ecosystems and digital innovation in food retailing: Exploring the rise of Hema in China	2021	Geoforum	Activity	Primary	Nexus
51	Wang, G., Henfridsson, O., Nandhakumar, J., & Yoo, Y.	Product Meaning in Digital Product Innovation	2022	MIS Quarterly	Activity	Primary	Nexus
52	Xing, F., Peng, G., Zhang, B., Li, S., & Liang, X.	Socio-technical barriers affecting large-scale deployment of AI-enabled wearable medical devices among the ageing population in China	2021	Technological Forecasting and Social Change	Activity	Primary	Nexus

Appendix B

Table A2
Coding and data structure.

Open Code/Examples		1st order Concepts	2nd order Themes	Aggerated Dimensions
physicality of interest: observation of interaction traces within physical environments	Bilgeri et al. (2019)	observation of physical interactions	**Activities**	**Facets of Physicality**
physicality of interest: observation of interaction traces within physical environments	Østerlie (2012)			
physicality of interest: characteristics of logics in smart cities	Cranefield and Pries-Heje, 2023			
physicality of interest: observation/control of smart environments	Tironi & Valderrama (2021)	manipulation of physical interactions		
physicality of interest: risk of physical interactions in medical settings	Oborn et al. (2021)			
physicality of interest: impact of technology on physical context	Ayre et al. (2019)	representation of physical interactions		
physicality of interest: design/characteristics of novel experiences	Wang et al. (2022)	experiencing of physical interactions		
physicality of interest: design of interactions between physical components	Marion & Fixson (2021)	designing of physical interactions		
physicality of interest: state of physical IoT environment	Monteiro & Parmiggiani (2019)	state of physical environments	**Artifacts**	
physicality of interest: requirements for the development of digital-physical products	Hendler & Boer (2019)	requirements of physical objects		
physicality of interest: perceived hedonic benefit of physical product characteristics	Kawakami & Parry (2015)	characteristics of physical objects		
physicality of interest: capabilities of 3D printing	Rayna & West (2023)			
focus of study: alignment of development practices	Hendler & Boer (2019)	management practices	**Secondary Theorization**	**Criticality to Theorizing**
focus of study: emergence of new understanding of phenomenological realities	Monteiro & Parmiggiani (2019)	knowledge creation processes		
focus of study: social frictions between actors in remote governance settings	Tironi & Valderrama (2021)	social relationships		
focus of study: utilizing data for process innovation	Bilgeri et al. (2019)	process and business innovation		
focus of study: dynamics of physical interactions	Oborn et al. (2021)	control of physical interactions	**Primary Theorization**	
focus of study: changing characteristics of physical phenomena through technology	Østerlie(2012)	characteristics of physical phenomena		

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Table A2 (*continued*)

Open Code/Examples		1st order Concepts	2nd order Themes	Aggerated Dimensions
focus of study: hedonic valuation of physical characteristics	Kawakami & Parry (2015)	characteristics of physical products		
focus of study: technical limitations to direct manufacturing via 3D printing	Rayna & West (2023)	physical limitations of technology		

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