CONNECTING THE PARTS WITH THE WHOLE: TOWARD AN INFORMATION ECOLOGY THEORY OF DIGITAL INNOVATION ECOSYSTEMS

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ABSTRACT

The remarkable connectivity and embeddedness of digital technologies enable innovations undertaken by a broad set of actors, often beyond organizational and industry boundaries, whose relationships mimic those of interdependent species in a natural ecosystem. These digital innovation ecosystems, if successful, can spawn countless innovations of substantial social and economic value, but are complex and prone to often surprising failure. Aiming to understand ecosystems as a new organizational form for digital innovations, I develop a theory that addresses an underexplored but important question: In a digital innovation ecosystem, how are the efforts of autonomous parties integrated into a coherent whole and what role do digital technologies play in this integration? By synthesizing ecological and information perspectives, this information ecology theory identifies several key functions that digital technologies serve in providing the information needed to support the interactions and tasks for innovation in ecosystems of varying scales. This theory contributes to digital innovation research new insights on managing part-whole relations, the role of digital technologies in innovation, and multilevel interactions in and across digital innovation ecosystems. The theory can also inspire the development of next-generation information systems for ecosystems as a new organizational form.

Keywords: Digital innovation, ecosystem, information, ecology, theory, holon

1 Andrew Burton-Jones, Susan Scott, and Sean Xin Xu were the accepting senior editors for this paper. Likoebe M. Maruping served as the associate editor.
INTRODUCTION

Having just celebrated the 50th anniversary of the Internet and the 30th anniversary of the World Wide Web in 2019, we are reminded how our world is increasingly connected thanks to these and other digital technologies. Besides their remarkable connectivity, digital technologies have also broken up monolithic product architectures by decoupling information from physical objects (Normann 2001) and thus made the latter senseable, associable, and programmable (Yoo 2010). As a result, modular designs (Baldwin and Clark 2000) have become popular as the components of a product can be made by different actors, some of whom are from different industries, and then integrated into a package for the customers. Accordingly, diverse actors' almost unlimited creativity generates countless innovations in products, services, processes, and business models at breathtaking speed. So the development and implementation of innovations often outgrow the boundary and capacity of a single organization. Instead, a broader set of actors bring their capabilities and knowledge together in a so-called "ecosystem," where the actors' interactions mimic the interdependent relationships among species in a natural ecosystem.

A digital innovation ecosystem is defined as a loosely-coupled set of autonomous actors (people and organizations who interact without hierarchical fiat) involved in the development and implementation of innovations enabled by digital technologies. Digital innovations in ecosystems are possible because digital technologies enable the division of labor. Further, ecosystems are becoming a desirable, or even necessary form of organizing digital innovations because the knowledge required to solve a particular problem is often located outside a firm and the cost of tapping external knowledge with digital technologies is rapidly declining (Baldwin 2012). However, despite the possibility, desirability, and even necessity of innovating in ecosystems, the innovation outcomes vary widely. On one hand, giants like Apple and Google
are orchestrating their respective ecosystems, each of which is joined by numerous application developers, accessory vendors, service providers, and users, rolling out lucrative innovations and amassing unprecedented wealth. On the other hand, many digital innovation ecosystems struggled and collapsed. For example, the ecosystem formed around the Symbian operating system accounted for over half of the global smartphone sales through 2008 (West and Wood 2014). Soon after, however, the Symbian company, operating system, and ecosystem all suffered a sudden decline and disappeared, due to the ecosystem's "unprecedented organizational and technical complexity," uncommitted partners, and divided leadership (West and Wood 2014). A recent study of 57 ecosystems in 11 sectors found that fewer than 15% of the ecosystems studied were sustainable (Reeves et al. 2019).

From the downfall of Symbian and similar anecdotes surfaces a paradox for digital innovation ecosystems: The more effectively digital technologies enable the division of labor, the more actors join the ecosystem with their skills and creativity, yet the more difficult it is for the actors to integrate their efforts, and the more likely the ecosystem fails (Cennamo and Santaló 2019; Tilson et al. 2010). Intrigued by this paradox, I reviewed the literature on ecosystems in Information Systems (IS) and Organization Studies (OS) and found that there has been substantial research on the digitally-enabled division of labor, but not much on the integration of efforts in ecosystems. On one hand, most studies of ecosystems examined the parts (e.g., the actors, and their relations and actions) of an ecosystem but overlooked the ecosystem as a whole. This imbalance may amplify an atomistic view of ecosystems that promotes a "winner-takes-all" mentality and opportunistic practices, which may undermine an ecosystem. On the other hand, the capabilities of information technology (IT) are well-known to facilitate coordination and integration in organizations (e.g., Argyres 1999). Yet how IT, especially its
contemporary form – digital technology, shape the integration of efforts in ecosystems has been speculated (Baldwin 2012; Sahaym et al. 2007) but rarely examined directly. Therefore, I attempt to solve the part-whole imbalance problem in this paper, organized under the overall research question: In a digital innovation ecosystem, how are the efforts of autonomous parties integrated into a coherent whole and what role do digital technologies play in this integration?

To address the question, after the literature review, the concept of holon from ecology is applied to theorize the part-whole relations in ecosystems of varying scales. This ecology lens exposes the complexity of ecosystems, which I suggest can be understood and managed with an information lens. Basically, digital technologies serve a few key functions to provide the information needed in the interactions and tasks for innovation in an ecosystem. Then the ecology and information lenses are combined to develop an information ecology theory. Next, the theory's three-fold contributions to digital innovation research are discussed: (1) a focus on the part-whole relations that balances the division of labor with the integration of efforts to sustain ecosystems; (2) an information view of how digital technologies shape innovations; and (3) a multilevel framework for understanding cross-level interactions within and across digital innovation ecosystems. The paper ends with suggestions on ecosystems as a new site for multiple streams of IS research.

LITERATURE ON DIGITAL INNOVATIONS AND ECOSYSTEMS

To begin with, I review the literature on digital innovations and on ecosystems.

Research on Digital Innovations

For over three decades, innovation has been a key phenomenon in the IS field. IS research has examined (1) IS innovation, the application of new IT, often developed by the internal IS departments, in organizations (Swanson 1994); (2) IT innovation, the adoption and
diffusion of new IT-based processes or products (Fichman 2004); and more recently (3) digital innovation, "the carrying out of new combinations of digital and physical components to produce novel products" (Yoo et al. 2010, p. 725). These new combinations, relying on digital technologies, can produce not only new products, but also new processes and business models. Therefore, this paper adopts a broader definition of digital innovation: "a product, process or business model that is perceived as new, requires significant changes on the part of adopters, and is embodied in or enabled by IT" (Fichman et al. 2014, p. 333). For example, drones, 3D printing, and the sharing economy represent digital innovations in the form of a product, process, and business model, respectively.

IS research on digital innovations has examined their initiation, development, implementation, exploitation, external competitive environment, internal organizational environment, and outcomes (Kohli and Melville 2019). Cutting across these themes are a few common attributes of digital innovations. First, most digital innovations consist of multiple components organized in a modular structure. While modularity, as a design principle, may be applied to any object, digital artifacts can apply modularity much wider and deeper than physical ones (Kallinikos et al. 2013). Modularity runs wider because digital artifacts are programmable and editable, allowing them to be developed and deployed widely, across organizational and industry boundaries (Kallinikos et al. 2013). Hence, digital innovations often blur or span boundaries (Constantiou et al. 2017; Nambisan et al. 2017). For example, the boundaries of the automobile industry have been blurred by innovations such as GPS, mobile phones, and autonomous vehicles (Nischak and Hanelt 2019). Meanwhile, modularity runs deeper in digital artifacts due to their granular constitution, allowing tracing down their functionalities to several layers of operations (Kallinikos et al. 2013). As a result, digital innovations are often multilevel
and structured in a "layered modular architecture" (Yoo et al. 2010).

Initially, the multiple levels at which digital innovations take place refer to the different layers of digital technologies and the products they enable such as devices, networks, services, and contents (Yoo et al. 2010). Further, the multiple levels may also correspond to the different scales of operations ranging from novel processes and products within the IS department (Swanson 1994) to new processes, products, and business models within and across organizations (Fichman et al. 2014). Moreover, due to the multiple components of digital innovations and the diverse actors and actions required to innovate with digital technologies, the alignment of diverse interests and coordination of autonomous yet interdependent actions are challenging, and thus shared cognition is crucial in managing digital innovations (Nambisan et al. 2017). Giving and making sense of a digital innovation require the undertaking of a collective of actors, often outside the primary providers or adopters of the focal innovation. Therefore, digital innovations, as ideas of various stakeholders (Rogers 2003), may exist at multiple levels of knowledge and learning (Swanson and Ramiller 1997; Wang and Ramiller 2009).

In sum, while the common attributes and architecture of digital artifacts provide generative conditions for innovations (Van Schewick 2010; Zittrain 2006), the complexity brought by the actors involved in a digital innovation, and their ideas, actions, and interactions pose significant management challenges. Even prior to the digital age, an innovation could generate a proliferation of ideas, actors, interactions, and relationships, which require the development of new organizational functions and roles to manage the complexity and interdependence (Van de Ven 1986). Digital innovations, often multilevel and boundary-spanning, require new forms of organizing the complex and interdependent relationships and interactions among the actors involved. Consequently, organizations may no longer be an
adequate level at which to study or manage digital innovations. As shown in the next section, ecosystems have emerged to be a new form for organizing innovations in the digital age (Furr et al. 2016), and a promising site for digital innovation research.

**Research on Ecosystems in Information Systems and Organization Studies**

To evaluate extant research on ecosystems, I first consulted recent reviews of the ecosystem literature (including Adner 2017; Autio and Thomas 2014; Bogers et al. 2019; Jacobides et al. 2018; McIntyre and Srinivasan 2017; Nischak et al. 2017; Shipilov and Gawer 2020). This consultation was followed by a systematic review of the ecosystem literature in IS and Organization Studies (OS), two related fields where the meaning and utilities of the term "ecosystem" have expanded significantly in the past 30 years.

**Literature Review Methods**

In IS, the literature review included the proceedings of *International Conference on Information Systems (ICIS)* and the eight journals in the "Senior Scholars' Basket of Journals." In OS, the review covered the proceedings of *Academy of Management Annual Meetings (AOM)* and six leading journals, including *Academy of Management Journal, Academy of Management Review, Administrative Science Quarterly, Organization Science, Organization Studies,* and *Strategic Management Journal, Management Science,* a premium journal that covers both IS and OS topics, was also included. Together, these 2 conferences and 15 journals represent the peer-reviewed publications in the two fields. If the title or abstract of an article published in any of the above outlets between 1990 and 2019 included the word "ecosystem," the article (if available) and its metadata (title, abstract, author, publication date, etc.) were downloaded. As a result, 490 articles met the above criteria and were collected for this literature review.

In addition, also added to the collection were the 42 articles from a recent review of the
ecosystem literature (Nischak et al. 2017), where the authors selected articles based on searching keywords (including "ecosystem" and "information technology" among others) in the abstracts of the articles in three prominent bibliographic databases (JSTOR, EBSCO, and AISeL). After eliminating 17 duplicate articles, a pool of 515 articles was created as a reasonable sample of extant knowledge about ecosystem in IS and OS.

A research assistant and I then read the abstracts of the articles in this collection and highlighted the ecosystem(s) mentioned in each abstract. We eliminated the articles in which the term "ecosystem" was used only tangentially or referred to natural ecosystems such as forests and fisheries. Finally, in order to understand the part-whole relations in and across ecosystems, we attempted to identify different types of ecosystems in the remaining articles. Specifically, we first highlighted the term(s) that each article's author(s) used to refer to the ecosystem(s) in the article: e.g., innovation ecosystem, platform ecosystem, business ecosystem, product ecosystem, entrepreneurial ecosystem, cloud computing ecosystem, mobile ecosystem, and so on. Second, due to the ambiguity associated with the terms "platform ecosystem" and "innovation ecosystem," which can be applied to multiple types and at different levels, we excluded these two terms. For the articles that used either the term "platform ecosystem" or the term "innovation ecosystem," we read further and determined if the platform or innovation in each article referred to a product, service, or business. For example, if the term "platform" or "innovation" referred to a product, then the platform/innovation ecosystem in the article was classified as a product ecosystem. As a result, we identified four levels of analysis where exist six types of ecosystems for managing innovations. Table 1 provides the definition of each type and explains each type's relation to innovation.
Table 1. Types of Ecosystems Related to Innovation at Different Levels of Analysis

<table>
<thead>
<tr>
<th>Ecosystem Type and Definition</th>
<th>Relation to Innovation</th>
<th>Sample Article</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intra-organizational Level</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Intra-organizational ecosystem consists of actors, business processes, technology and other resources within an organization, coevolving to obtain organizational goals.</td>
<td>Interactions among internal actors may result in innovations in the products and processes within the organization.</td>
<td>(Vidgen and Wang 2006)</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Product/service Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product ecosystem includes the providers of a focal product, and the complementary products and services needed to create a whole solution for the customers to buy.</td>
<td>The focal product, or any of its complementary products or services in the ecosystem may embody innovation.</td>
<td>(Foerderer et al. 2018; Lueker et al. 2018)</td>
<td>21%</td>
</tr>
<tr>
<td>Service ecosystem is self-contained adaptive system of actors interacting to exchange service by integrating their or others' resources.</td>
<td>The ecosystem can foster a new service or new ways to exchange the service.</td>
<td>(Lusch and Nambisan 2015; Vargo and Akaka 2012)</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Business Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Business ecosystem includes all stakeholders whose actions influence the focal firm's business.</td>
<td>Stakeholders in the ecosystem can shape innovations in the processes, products, services, and/or business model of the focal firm.</td>
<td>(Hannah and Eisenhardt 2018; Iansiti and Levien 2004)</td>
<td>37%</td>
</tr>
<tr>
<td>Entrepreneurial ecosystem refers to the business ecosystem, often anchored in a geographic region, for a new venture.</td>
<td>The ecosystem supports entrepreneurs and other actors to establish and fund a new venture.</td>
<td>(Du et al. 2018; Giudici et al. 2018)</td>
<td>28%</td>
</tr>
<tr>
<td><strong>Category Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category ecosystem encompasses stakeholders involved in the production and/or use of a category of products, services, technologies, or businesses.</td>
<td>An innovation as a new category of products, services, technologies or businesses is interpreted, legitimized, and actualized in the ecosystem.</td>
<td>(Adomavicius et al. 2008; Basole 2009)</td>
<td>6%</td>
</tr>
</tbody>
</table>

* This is the percentage of the articles that examined each type of ecosystems in all articles reviewed. Some articles examined two or more types per article, thus the percentages add up to more than 100%.

**Innovation Ecosystems at Multiple Levels**

At the intra-organizational level, the lowest level in the literature review, "business process ecosystems" consist of coevolving users, business processes, IT developers, and software (Vidgen and Wang 2006). Moving up a level to the product/service level, a "product ecosystem" includes not only the provider of a focal product, but also the providers of complementary products and services (e.g., training and support), and/or other parties needed to create a whole solution for customers to buy (Frels et al. 2003). In contrast, "service ecosystems" are self-organizing systems of actors who co-create value in their service exchanges (Vargo and Akaka 2012, p. 207).

The next is the business level. A "business ecosystem" centers around a focal firm and
includes the stakeholders whose actions affect the focal firm's business. Also at this level are "entrepreneurial ecosystems" with an explicit emphasis on new ventures. The highest level in the literature review is the category level, where a "category ecosystem" emerges around a market category of products, services, or technologies, and thus may include several ecosystems of products, services, or businesses. Therefore, "mobile ecosystems" and "cloud computing ecosystems," for instance, exemplify "category ecosystems." In sum, this literature review suggests that innovations may take place in ecosystems that are formed to manage them at multiple levels.

**Part-Whole Imbalance**

Unfortunately, in the IS and OS literature on ecosystems there has been an imbalance favoring the "parts" over the "whole" of an ecosystem in empirical studies. This part-whole imbalance is reflected in two ways. On one hand, most of the ecosystem studies in the literature review are single-level research. A majority of the papers in the collection examined the relationships and interactions among the actors in product/service or business ecosystems, without considering any attribute of the ecosystems. Admittedly, numerous studies examined the interactions between an ecosystem sponsor and the participants of the ecosystem, but these studies are essentially single-level because the sponsor, however dominant in its ecosystem, is not the same as the ecosystem.

On the other hand, a few studies did examine the whole ecosystem. However, most of

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2 In this literature review, when a firm sponsors more than one product ecosystem (e.g., Amazon sponsoring the AWS Marketplace ecosystem for cloud computing and the Amazon Marketplace ecosystem for e-commerce), the firm's business ecosystem is different from (albeit connected with) the product ecosystems the firm sponsors. When a firm sponsors just one product ecosystem (e.g., eBay sponsoring its e-commerce ecosystem), the ecosystem is recognized as a business ecosystem, to avoid confusing the business level with the product level.

3 Of the empirical studies that examined product/service or business ecosystems, 69% did not mention any attribute of the ecosystem in the abstracts. For example, in a business ecosystem, coopetition (cooperation + competition) and value distribution among the participants have been enduring themes. Yet few studies (e.g., only 8% articles on business ecosystems in the collection) evaluated the overall performance of the ecosystem examined in each study.
these studies are firm-centric, treating the ecosystem as an exogenous context that is either fixed or out of the participants' control. For example, nearly one quarter of the articles about product ecosystems included some attributes of the ecosystems in the analysis but only about 10% treated the ecosystem attributes as outcomes, with the rest focused on firm-level outcomes (e.g., sales/profits).

This part-whole imbalance is not surprising. Understandably, the emphasis on the division of labor implied in modular designs directs management attention towards the parts, away from the whole (Van de Ven 1986). The parts of an ecosystems (e.g. platform owners, complementors, adopters, and the products or services they develop or use) are more visible, and thus easier to study, than the whole of the ecosystem, which is largely intangible. After all, multilevel research is more difficult to do than single-level studies (Klein and Kozlowski 2000).

However, this part-whole imbalance runs the risks of undermining both the research and practice of digital innovations in ecosystems. For research, at least two types of fallacies, as described by Burton-Jones and Gallivan (2007) may occur in single-level studies of multilevel phenomena like digital innovations. First, contextual fallacy may result from spurious relationships at a lower level. For example, the effect of innovation on firm performance may be moderated by the competition at the ecosystem level (Wang et al. 2020). Second, the mechanisms by which entities at different levels interact may be neglected, leading to cross-level fallacies. For example, how an ecosystem as a whole and its parts interact and how ecosystems at different levels interact are questions underexplored yet important for understanding the multilevel nature of digital innovations and their ecosystems. For practice, focusing only on the "parts" may promote an atomistic view of ecosystem management, prompting managers to pay attention to only the respective parts within their managerial purview, losing sight of the whole
picture. Consequently, this atomistic view may overemphasize the mechanisms and forces that favor division over integration, driving an ecosystem to collapse into separate entities without synergy (Baldwin 2020). Even worse, the bias towards parts carries implicitly a "winner-takes-all" mentality (Katri et al. 2017), as a typical study often takes the perspective of one participant (often the platform owner or ecosystem sponsor) or one group of participants (e.g., third-party app developers) and evaluates their "value capture" strategies, as if in zero-sum games, to maximize individual gains. Where fairness and balance are needed to sustain healthy and thriving ecosystems, favoring the parts over the whole would be troublesome or even dangerous.

Solving the part-whole imbalance problem would require theorizing beyond the scope of the literature review. In this theory development, I will take ecology and information perspectives to explore the part-whole relations (1) between the actors and their ecosystem and (2) among ecosystems at different levels. Along the way, four specific research questions (SRQs) about these part-whole relations will be raised and addressed. The point of departure for this theorizing journey is ecology, which inspired ecosystem research from the very beginning.

**ECOLOGY LENS: LINKING THE PARTS WITH THE WHOLE**

As Wilber (2017) wrote: "You can take a watch apart and analyze its parts, but they won't tell you the time of the day" (p. 22). Even if every element of a digital innovation ecosystem has been analyzed, that does not necessarily mean that we have understood the ecosystem as a whole. Since an ecosystem can shape its members (e.g., Mantovani and Ruiz-Aliseda 2016), it is useful to understand a digital innovation ecosystem as a whole and its relationship with its parts.

Ecologists have examined the part-whole relations in natural ecosystems in their attempts to understand the interactions between physical environment and the biosphere (Allen and Starr 2017) and to determine humanity's place in nature (Esbjorn-Hargens et al. 2011). Some
ecologists draw on the concept of *holon* (Koestler 1967; Koestler 1979) to conceptualize how part-whole relations emerge and evolve at different levels of the biological hierarchy.\(^4\)

**Holon and Holarchy: Ecological Conceptualization of Part-Whole Relations**

Over 50 years ago Koestler (1967) noticed the gap between the reductionist approach and the holistic approach to understanding complex systems. He attributed the problem to the ambiguity of the terms "part" and "whole" when applied to hierarchies. The ambiguity, according to Koestler, stems from the fact that neither "wholes" nor "parts" exist in an absolute sense, but that an entity in a hierarchy displays both characteristics commonly attributed to "wholes" and characteristics commonly attributed to "parts," depending on the perspective of the observer. For example, each individual is an integrated "whole" enjoying his/her freedom. Meanwhile, each individual is also a "part" of a community or society where no one should exercise his/her freedom by jeopardizing others' safety. Considering this duality, Koestler coined the term *holon*, combining the Greek word "holos" (meaning whole) and suffix "on" (suggesting a particle or part), and used holons to designate "nodes on the hierarchical tree which behave partly as wholes, or wholly as parts, according to the way you look at them" (Koestler 1967, p. 48). Each holon, like the Roman god Janus, has two faces looking at opposite directions: one facing the lower level representing a complete whole and the other facing the upper level representing a dependent part (Koestler 1967). Further, because the word "hierarchy" connotes authoritarian, rigid structure, Koestler coined "holarchy" to refer to a hierarchy of "autonomous, self-governing holons endowed with varying degrees of flexibility and freedom" (Koestler 1979, p. 34).

Ecologists have found the concept of holon appealing as the biological hierarchy from

\(^4\) Part-whole, or meronymic, relations have also been examined in other fields, such as linguistics (Gerstl and Pribbenow 1995), psychology (Winston et al. 1987), artificial intelligence (Girju et al. 2006), philosophy (Varzi 1996), and IS development (Shanks et al. 2008), where the primary focus seems to have been on the representation or type of these relations, rather than the interactions stemming from the relations.
individual organisms to the global biosphere can be conceptualized as a holarchy of holons (Esbjorn-Hargens et al. 2011). At each level, each holon is both a whole, composed of the parts at the level below, and a part of a more inclusive whole at the level above. For instance, an ecological community consisting of multiple species of organisms belongs to a broader ecosystem. As a holon, the community has two faces. As a whole, the community displays the self-assertive tendency with its autonomy. Meanwhile, the community, as a part of an ecosystem, shows its integrative tendency by meeting the resource constraints set by the conditions of the ecosystem.

While the concept of holon helps ecologists connect the parts with the whole across the biological hierarchy, the concept of holon has been generalized to represent entities beyond ecology (Allen and Starr 2017; Wilber 2017). For example, human, family, community, and nation are holons in a social holarchy; letter, word, phrase, and sentence are holons in a linguistic holarchy. Essentially, the concept of holon offers both useful terminology and generalizable insights that can be applied to understand the part-whole relations in digital innovation ecosystems.

As Figure 1 illustrates, diverse entities involved in various types of digital innovations may appear as holons at different levels of a "holarchy of digital innovation ecosystems." At the bottom, intra-organizational ecosystems are parts of organizations, which are parts of industries. Individual and organizational actors from different industries are parts of a product or service ecosystem, which may be a part of a business or entrepreneurial ecosystem, as the examples of

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5 The characterization of holons in a hierarchical ordering scheme is consistent with General Systems Theory (Von Bertalanffy 1972), which inspired systems thinking in many fields, including both ecology (Willis 1997) and IS (Churchman 1968; Churchman 1979), in the second half of the 20th century. I chose the concept of holon to theorize the part-whole relations not only because it is intuitive and concrete, but also due to its dual focus on both the parts and the whole and thus the possibility of an entity to shape its environment.
Amazon, eBay, and Alibaba in the figure illustrate. Near the top of the holarchy, product/service ecosystems and business ecosystems are parts of category ecosystems, which, in turn, may constitute the business or technology landscape. Taken together, Figure 1 shows a holarchy of holons connected by a variety of part-whole relations for digital innovations at multiple levels.

In addition, Koestler and others have articulated scores of principles to describe how the activities of holons are governed by such part-whole, or holonic, relations (Allen and Starr 2017; Esbjorn-Hargens et al. 2011; Koestler 1967; Koestler 1979; Wilber 2017). Some of the principles of holon can be applied to raise a few specific research questions aimed at addressing this study's overall research question regarding the part-whole integration in digital innovation ecosystems.

**Part-Whole Relations within an Ecosystem**

Within an ecosystem, a digital innovation may manifest itself as a structure (e.g., pattern
of actions or interactions) and function (e.g., outcome as a result of the innovation) at the levels of both the parts and the whole. Regarding innovation structure, at the level of the parts, actors innovate by changing their processes, products, or business models. If they do so independently without any interactions among themselves, then there is no innovation at the level of the whole. However, there is hardly any isolated innovator or stand-alone innovation (Rogers 2003) or a holon being just a part or just a whole (Wilber 2017). The actors' interdependencies and interactions give rise to an ecosystem as a structure for aligning the interdependencies and coordinating the interactions without the fiat or contracts commonly seen in hierarchical organizations and markets, respectively. Because of these interdependencies, interactions and the ensuing alignment and coordination structure, the innovation takes shape as an integrated process, product, business model, or category at the level of the whole ecosystem.

Essentially, a holarchy is a flexible network of interactions among interdependent holons with self-assertive and integrative tendencies. According to a principle of holon, "every holon has the dual tendency to preserve and assert its individuality as a quasi-autonomous whole; and to function as an integrated part of an (existing or evolving) larger whole" (Koestler 1967, p. 343). Due to the integrative tendency of the holons, the actions and interactions of the actors in an innovation ecosystem can be integrated, according to certain top-down rules (e.g., access and exclusivity), into the innovation at the ecosystem level. Due to the self-assertive tendency of the holons, the structure of an ecosystem emerges in a bottom-up process characterized by heterogeneous patterns of interactions among the actors.

While ecosystem research has begun to examine the top-down effects of ecosystem structure on the actors (Adner 2017; Zhu and Iansiti 2019), there is much to learn about how different ecosystem structures emerge from the interactions among actors with both self-assertive
and integrative tendencies. The process of such bottom-up emergence is crucial to the understanding of not just ecosystem structure, but also how ecosystems function, as will be discussed next. For example, when a focal product provider dictates how complementary products must be made in a product ecosystem and reaps most of the profit from selling the product package (Cennamo 2014), the provider's self-assertive tendency is expressed with almost no limit and its integrative tendency is forgotten. This out-of-balance situation may cause the ecosystem to collapse. While this may seem like an extreme case, it illustrates the need to manage the part-whole relations in a digital innovation ecosystem - hence the first specific research question:

**SRQ1:** *In a digital innovation ecosystem, how does an innovation as a whole emerge from the interactions of the actors in the ecosystem?*

Regarding the function of an innovation in an ecosystem, at the level of the parts, actors engage with an innovation to pursue specific goals that they value. Their performances may be indicated by the outcomes of their innovation activities. It becomes clear that, viewed from the level of the whole ecosystem however, different actors pursue different goals, and thus the innovation outcomes vary depending on the specific perspective of a specific actor. Therefore, each actor's engagement with the innovation may help the actor achieve its own goal and realize the *intrinsic* value of the innovation for itself. At the level of the whole ecosystem, each actor's engagement with the innovation may be conducive to other actors' pursuits of their respective goals, thus realizing the *extrinsic* value of the innovation for others. According to another principle of holon, "every holon has intrinsic value, or the value of its own particular wholeness. Each holon has extrinsic value, instrumental value, value for other holons" (Wilber 2017, p. 302). Without realizing the intrinsic value, the actor would lose interest and leave the ecosystem.
Without offering extrinsic value, it would be difficult for others to join or stay in the ecosystem. Therefore, the performance of an ecosystem is the degree to which both the intrinsic and extrinsic values of the focal innovation are realized by the actors in the ecosystem.

For these reasons, it is intuitive to think that the performance of an ecosystem and the performances of the actors in the ecosystem depend on each other. However, the nature and mechanisms of such part-whole interdependence remain to be explored. On one hand, the performances of the actors may be reflected in their differentiated goals achieved or values realized, such as profitability for vendors, employee productivity for user organizations, and social benefits for nonprofits. On the other hand, the performance of an ecosystem may be reflected too from different perspectives such as health, productivity, robustness (Iansiti and Richards 2006), resilience, scalability, durability (Tiwana 2013), and so on. It is not clear how the different aspects of the performance at the actor level constitute which aspect of the performance at the ecosystem level, or how the ecosystem performance shapes which aspect of the actors' performances. Even for the same aspect of performance, for instance, profitability, varying levels of actors' commitments and different types of complementarities (Jacobides et al. 2018) may lead to different forms and degrees of part-whole interdependencies.

**SRQ2: How do the performance of a digital innovation ecosystem and the performances of the actors in the ecosystem depend on each other?**

**Part-Whole Relations among Ecosystems**

Part-whole relations exist not only within an ecosystem, but also among ecosystems, because every ecosystem, as a holon itself, behaves as an integrated whole and dependent part at the same time. For example, the ecosystems for Amazon's e-commerce and cloud computing services are integral parts of Amazon's business ecosystem. Further, the category ecosystem for
cloud computing, for example, consists of the product or business ecosystems of Amazon, Alibaba, and other cloud providers. In our collection of articles, fewer than 3% examined inter-ecosystemic interactions. Nevertheless, the part-whole relations among ecosystems are no less complex or less important than those within an ecosystem. Research is needed to inform critical decisions on the ecosystems to sponsor (Jacobides 2019) or participate in (Bender and Gronau 2017), and on the market category to join (Hannan et al. 2019).

The concepts of holon and holarchy provides helpful insights into inter-ecosystemic interactions as well. Regarding the structure of innovations across ecosystems, consider the following principle: "Holons emerge holarchically. Each emergent holon transcends but includes its predecessor" (Wilber 2017, p. 335). Accordingly, the product ecosystems related to a focal firm may evolve into a business ecosystem, which transcends and includes the participating product ecosystems. Business ecosystems and the embedded product ecosystems may evolve into a category ecosystem, which transcends and includes the participating ecosystems at lower levels. Inclusion means that, as new ecosystems emerge at higher levels, the ecosystems at lower levels that help these new ecosystems emerge continue to exist; they are included in the new ecosystems. Regarding the meaning of transcendence, in a business ecosystem, a transcending principle may be the focal firm's strategy on the product or service ecosystems to sponsor or join. In a category ecosystem, a transcending principle may be reflected in a set of overarching ideas, dubbed "organizing vision" (Swanson and Ramiller 1997), for organizing the development and implementation of the innovative products or services in that category. Although inclusion and transcendence involve both bottom-up and top-down processes, top-down processes such as modularization and centralized governance are closely related to the division of labor. In contrast, as foreshadowed by this study's overall research question about the integration of
efforts, much remains to be explored about the bottom-up processes by which higher-level ecosystems emerge from, transcend, and include lower-level ecosystems for digital innovations. **SRQ3:** *How does a digital innovation in a higher-level ecosystem emerge from the innovations in lower-level ecosystems?*

Regarding the function of innovations across ecosystems, the performances of ecosystems at different levels may be interdependent, just as the performances of an ecosystem and its actors depend on each other. However, research is even scarcer on the interactions of ecosystems at different levels. For example, it is not clear how a business ecosystem's performance reflects the performances of the product or service ecosystems that constitute the business ecosystem. Similarly unclear is how a category ecosystem's performance (however measured) may shape the performances of the business, entrepreneurial, product, and service ecosystems that fall into the category. As more people and organizations are usually involved in multiple ecosystems than in a single ecosystem, the interdependence of ecosystem performances is more complex yet more important to understand. Hence, **SRQ4:** *How do the performance of a digital innovation ecosystem at a higher level and the performances of digital innovation ecosystems at a lower level depend on each other?*

In summary, the part-whole relations within and across digital innovation ecosystems can be conceptualized along a holarchy of holons. Although the ecology lens has helped raise four specific research questions about part-whole interactions (summarized in Table 2), ecology alone cannot help answer these questions. In fact, the ecology lens has exposed more complexity, interdependencies, and uncertainties associated with a vast number of actors at stake, demonstrating the difficulty in understanding or managing the part-whole relations within and across ecosystems. This challenge, as explained in the next section, may be addressed with an
Table 2. Research Questions about Part-Whole Relations in Digital Innovation Ecosystems

<table>
<thead>
<tr>
<th>Intra-ecosystemic Interactions</th>
<th>Structure of Innovation</th>
<th>Function of Innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRQ1: In a digital innovation ecosystem, how does an innovation as a whole emerge from the interactions of the actors in the ecosystem?</td>
<td>SRQ2: How do the performance of a digital innovation ecosystem and the performances of the actors in the ecosystem depend on each other?</td>
<td></td>
</tr>
<tr>
<td>SRQ3: How does a digital innovation in a higher-level ecosystem emerge from the innovations in lower-level ecosystems?</td>
<td>SRQ4: How do the performance of a digital innovation ecosystem at a higher level and the performances of digital innovation ecosystems at a lower level depend on each other?</td>
<td></td>
</tr>
</tbody>
</table>

INFORMATION LENS: INFORMING PART-WHOLE INTERACTIONS

As an organizational form for innovation, ecosystems involve broader sets of actors than conventional organizations and thus the complexity of an ecosystem usually exceeds that of a traditional organization. This complexity, if not understood and managed, may undermine ecosystems as a useful way to organize innovations. Much of the complexity comes from the interdependencies among the actors in an ecosystem. On one hand, while modular designs generally reduce the interdependencies among the tasks undertaken by the producers of complementary modules (Baldwin and Clark 2000; Gawer and Cusumano 2014), the multiple layers of complementary products can increase task interdependencies (Kapoor and Agarwal 2017). On the other hand, the benefits of the focal innovation can be realized only if all actors complete their tasks without holdouts or bottlenecks. In other words, the actors face broad incentives and thus their rewards are interdependent (Puranam et al. 2012). Both task and reward interdependencies can cause significant uncertainties in the decision making by every actor involved. For example, when it is difficult to create a meaningful vision for the innovation ex ante (Dattée et al. 2018), actors may be uncertain about (1) whose tasks depend on their own tasks, or (2) on whose tasks their own tasks depend. Too, when facing broad incentives, actors may be uncertain about others' actions but sometimes they have to act before others (Puranam et
Taken together, the complexity, interdependencies, and uncertainties require that relevant information be collected to inform decision-making in the ecosystem. But what information is relevant? And how to satisfy the need for such information?

**Information Needed for Innovation Decision Making**

Organizations need information (and information systems) to facilitate and shape the interactions within and among organizations (Swanson 2007). In an ecosystem, information is also needed to facilitate and shape the interactions. Given diverse actors in different types of ecosystems, it would be difficult to compile an exhaustive list of information that the actors need for their interactions. Nonetheless, IS research has developed useful taxonomies of information that can be applied to recognize the information needed in digital innovation ecosystems (Boell 2017; Emamjome et al. 2018; McKinney Jr. and Yoos II 2010; Mingers and Standing 2018).

For example, McKinney Jr. and Yoos II (2010) identified four views of information: (1) information in the "token" view is data subject to processing; (2) information in the "syntax" view is a measured relationship among tokens; (3) information in the "representation" view is a sign of an object to an observer; and (4) information in the "adaptation" view is a perceived difference leading to change. Although actors need information in all four views to develop and implement innovations in an ecosystem, most relevant to managing part-whole relations and the ensuing complexity, interdependencies, and uncertainties is information in the representation and adaptation views. This is because these two views of information can help actors align their diverse interests and coordinate their actions in the ecosystem.

Regarding alignment, actors need to know how their interests and efforts fit into a collective structure, which may take such forms as a value proposition (Adner 2017), blueprint for the vendors (Dattée et al. 2018), or product architecture (Ulrich 1995). Regardless of its
specific label, an alignment structure (sign) represents a model of the innovation (object) to an actor (observer), as the structure conveys information that the actor can use when it interacts with other actors and with the ecosystem as a whole. For example, an ecosystem sponsor may use the information about the product architecture (created by the sponsor or through negotiation) to divide the responsibilities of making product modules or complements. As a result of such informed decision making, the sponsor may accumulate architectural knowledge (Puranam et al. 2012) that can be applied to reduce the complexity stemming from the interdependencies among the complementors. Essentially, the alignment structure conveys information in the representation view, which "re-presents" the part-whole relations and helps actors develop architectural knowledge for managing interdependencies in the ecosystem.

Regarding coordination, due to the interdependencies described above, each actor must decide whether, when, and how to take action based on the information about other actors and their actions, so they can coordinate their innovation efforts. Much of the information about other actors is based on the focal actor's perception of those actors and prediction of those actors' reactions to the focal actor's actions. In other words, the actor adapts to the reality it perceives and to the future it predicts. Information in the adaptation view can help actors develop predictive knowledge about other actors and avoid coordination problems and failures.

In sum, information about alignment structure and other actors is relevant to the focal actor, as it needs this information to make decisions, given the interdependencies and uncertainty in the complex ecosystem. How this need for information is satisfied, as discussed next, depends on the information capacity of the digital innovation ecosystem.

**Matching Information Needs with Information Capacity**

To understand how to satisfy the information needs for managing part-whole relations in
ecosystems, I draw on the organization design (OD) literature because a notable tenet of that literature is that modes of organizing differ in their capacity to process information (Galbraith 1974; Puranam et al. 2012; Tushman and Nadler 1978). Within an organization, integrating the different parts (e.g., departments, functions, groups, etc.) into a synergistic whole requires an alignment structure and coordination mechanisms such as rules, hierarchical referrals, and goals (Galbraith 1974). As new parts are added (due to innovation), uncertainties about and interdependencies among the parts increase. So there is a need for more information (Galbraith 1974). An organization's information need should match the information capacity of the organization's structure, in order to deliver effective organizational performance, according to a central thesis of OD (Tushman and Nadler 1978). Information capacity refers to the capabilities to inform, specifically, to collect, process, store, and distribute information, essentially the functions of information systems (Piccoli and Pigni 2019). To boost its information capacity, the organization can invest in information technology and/or create lateral relations such as liaison roles, task forces, teams, or matrix organization (Galbraith 1974). Although OD researchers acknowledge the utilities of IT, they assume that IT suits the need for only formal information (Galbraith 1974; Tushman and Nadler 1978) and thus focus on organizational structures as the main components of design strategies. IS researchers, on the other hand, have paid only sporadic attention to the role of IT in OD (Lucas and Baroudi 1994; Stebbins et al. 1995). This is a missed opportunity considering the remarkable advancements of IT, capable of supplying information in numerous formats (Boell 2017; McKinney Jr. and Yoos II 2010).

The rise of ecosystems as a new form of organizing innovations provides an opportunity

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6 Organization design researchers often use the term "information processing" (Baldwin 2012; Galbraith 1974; Simon 1973; Tushman and Nadler 1978), but it also refers narrowly to "data processing" in IS research (McKinney Jr. and Yoos II 2010). Therefore, I have dropped the word "processing," which might cause confusion, and adopted the term "information capacity" to refer broadly to the capabilities to inform.
to understand the role of IT in augmenting information capacity. However, when applying OD insights to ecosystems, a couple of design issues unique for ecosystems are notable. For one, as described above, all actors in an ecosystem faces broad incentives and thus their rewards are interdependent (even if their tasks might not). This additional interdependence increases uncertainties and thus the need for information. For another, while OD is usually conducted by a consultant or senior manager and implemented with top-down approaches, every actor in an ecosystem is autonomous and thus a designer, making its own decisions on whether and how to participate in a specific ecosystem. Consequently, the structure of the ecosystem is constantly changing as actors make their own engagement decisions. The dynamic nature of ecosystems makes it desirable or even necessary to employ IT (in addition to lateral relations, the traditional focus of OD) to meet the information needs in managing part-whole relations in ecosystems.

In sum, digital innovation ecosystems provide an opportunity to explore how IT, specifically its contemporary form – digital technologies, can match an ecosystem's information capacity with the information needs in integrating the parts into the whole ecosystem.

**Satisfying Information Needs with Digital Technologies**

To explore how digital technologies affect an ecosystem's information capacity, the collection of articles in the above literature review was reused. I searched "innovate" and "innovation" in the articles' titles or abstracts and identified nearly 200 articles that explicitly discussed innovation issues in ecosystems. A research assistant and I read the full text of these articles (if available) and annotated specific part-whole interactions (first-order categories) among the actors in the ecosystems. Based on the commonalities of the interactions, we grouped them into 11 innovation tasks (second-order themes), and further into 4 general dimensions. Figure 2 shows this induction process, which is detailed below following the order of the SRQs.
raised above. In addition, we identified the specific digital technologies used (if described in the articles) for these interactions and tasks. To theorize the role of digital technologies, we adapted a widely cited list of attributes that Yoo (2010) created to characterize digitalized artifacts and identified six functions of digital technologies: programming, sensing, communication, memory, tracing, and association, which correspond to the attributes of digital artifacts Yoo (2010) identified.7

Structure of Innovation within an Ecosystem

SRQ1 pertains to the emergence of a digital innovation as a whole from the interactions of the actors in the ecosystem. These interactions, as Figure 2 shows, help accomplish a few tasks that lead ultimately to the integration of innovations at the ecosystem level. Foremost, such integration depends on the task of "sharing." Digital artifacts such as software code and codified knowledge are shared among the actors in the ecosystems. Sometimes the sharing is open, such as in the case where the German e-commerce firm Otto made its platform's source code publicly available (Fürstenau et al. 2019). At other times the sharing is between specific parties, as in a Singaporean telemedicine ecosystem where neurologist expertise was shared by the hub hospital with satellite hospitals (Taani and Faik 2019). Digital technologies make the sharing easy: Version control systems such as GitHub served as memories of source code for asynchronous sharing (Fürstenau et al. 2019); and telecommunication systems facilitated real-time sharing of surgical images and videos (Taani and Faik 2019). As a result, information is created from this sharing. For example, code and algorithm, as representations of the e-commerce business processes, were information in the representation view, which might be used by others to

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7 Another attribute, "addressable," in Yoo's (2010) list does not correspond to a technological function that can be identified reliably in the ecosystem literature.
develop innovative shopping features (Fürstenau et al. 2019). Sharing seems to rely at least on the technological function of memory.

<table>
<thead>
<tr>
<th>Part/Whole Interactions (First-order Categories)</th>
<th>Innovation Tasks (Second-order Themes)</th>
<th>Innovation Tasks (Aggregate Dimensions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Sharing code/program</td>
<td>Sharing</td>
<td>Integration</td>
</tr>
<tr>
<td>• Sharing expertise</td>
<td>Combining</td>
<td></td>
</tr>
<tr>
<td>• Sharing knowledge</td>
<td>Standardizing</td>
<td></td>
</tr>
<tr>
<td>• Combining digital components to create products</td>
<td>Co-creating</td>
<td>Value Realization</td>
</tr>
<tr>
<td>• Reusing or recombining capabilities</td>
<td>Multi-homing</td>
<td></td>
</tr>
<tr>
<td>• Following standard or de facto standard</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Developing standard by pooling innovations</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Developing standard via consortium</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Orchestrating multiple ecosystems</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Participating in multiple ecosystems</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Integrating apps &amp; systems by adopters</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Developing complementary product/service</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Enhancing user experience</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Making sense of product/service</td>
<td>Co-creating</td>
<td></td>
</tr>
<tr>
<td>• Sharing revenue</td>
<td>Appropriating</td>
<td></td>
</tr>
<tr>
<td>• Copying product designs and features among actors</td>
<td>Appropriating</td>
<td></td>
</tr>
<tr>
<td>• Coring functionality by ecosystem sponsor</td>
<td>Appropriating</td>
<td></td>
</tr>
<tr>
<td>• Assessing market demand by listening to customers</td>
<td>Searching</td>
<td></td>
</tr>
<tr>
<td>• Networking to identify business opportunities</td>
<td>Searching</td>
<td></td>
</tr>
<tr>
<td>• Looking for external resources &amp; capabilities</td>
<td>Searching</td>
<td></td>
</tr>
<tr>
<td>• Parallel experimenting</td>
<td>Experimenting</td>
<td>Adaptation</td>
</tr>
<tr>
<td>• Sequential experimenting</td>
<td>Experimenting</td>
<td></td>
</tr>
<tr>
<td>• Updating product to improve technology and meet demand</td>
<td>Updating</td>
<td></td>
</tr>
<tr>
<td>• Regularizing &amp; accelerating product updates</td>
<td>Updating</td>
<td></td>
</tr>
<tr>
<td>• Screening complementary products by sponsor</td>
<td>Controlling</td>
<td>Moderation</td>
</tr>
<tr>
<td>• Executing rules codified in smart contracts</td>
<td>Controlling</td>
<td></td>
</tr>
<tr>
<td>• Selecting specific products to endorse</td>
<td>Promoting</td>
<td></td>
</tr>
<tr>
<td>• Cross-selling products</td>
<td>Promoting</td>
<td></td>
</tr>
<tr>
<td>• Recommending specific products to specific customers</td>
<td>Promoting</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Interactions and Innovation Tasks in Digital Innovation Ecosystems
The second integration task is "combining," referring to the process of mixing the elements originally belonging to different actors to form something new. For example, in the ecosystem for WordPress, an open source content management system, third-party developers combined software components that implemented application programming interfaces (APIs) to create "plug-ins" (Um et al. 2015). More broadly, Sony Ericsson, a mobile phone maker, reused and recombined innovation capabilities from different layers of the Android mobile operating system (Selander et al. 2013). The layered modular architecture of digital technologies made such combinations possible: Programmable modules such as software code and mobile apps, created by third-party developers, were combined to create innovative products or services. In these cases, digital technologies such as API and mobile operating systems helped link programmable artifacts, generating information such as the architecture of WordPress and Android (information in the representation view) that actors might use to combine or recombine. Apparently, the technological function of programming supported primarily the combining task.

Despite its complex structure, an ecosystem can lessen its complexity through the actors' "standardizing," the third integration task found in this analysis. On one hand, the actors in ecosystems follow standards or de facto ones. For example, some developers of the extensions for Mozilla's Firefox faithfully used the interface standards, explicitly codified reference designs and app design best practices prescribed by the platform owner Mozilla (Tiwana 2015b). On the other hand, both the producers and users of innovations sometimes take proactive roles in developing standards in an ecosystem. For example, the providers of digital television technologies pooled their patents to promote standards on a certain technology (e.g., MPEG-2) by licensing patents to one another and to third parties (Vakili 2016). Various digital technologies support standardization: Extensible Markup Language (XML) enabled the
exchange of data across different computer systems in the newsrooms (Rolland et al. 2018); and APIs and various protocols formed the basis for browser interface standards (Tiwana 2015b). Standardizing, both setting and following standards, can lower an ecosystem's complexity by reducing the interdependencies among the actors in the ecosystem, coordination costs (Tiwana 2015b), as well as uncertainties and the need for information processing, because each actor's engagement with the innovation would be more predictable, anchored around the standards.

Summarizing, three tasks (sharing, combining, and standardizing) have thus far been identified that induce part-whole integration within a digital innovation ecosystem, where various digital technologies help match the need for information with the ecosystem's information capacity. Specifically, responding to SRQ1,

**Proposition 1:** *In a digital innovation ecosystem, the innovation as a whole can be integrated through actors' sharing, combining, and standardizing. Digital technologies support sharing and combining with their memory and programming functions, respectively, increasing the ecosystem's information capacity; whereas standardizing reduces the need for information processing.*

Figure 3 positions the integration task (and Proposition 1) in a broader depiction of the interactions and tasks within a digital innovation ecosystem to be explored further below.

![Figure 3. Interactions and Innovation Tasks in a Digital Innovation Ecosystem](image-url)
Shifting from the structure of digital innovations to their functions, I now address SRQ2 about the relationship between an ecosystem's performance and the performances of actors in the ecosystem. The first to be considered is an actor's performance as the outcome of the actor's pursuit of the innovation's intrinsic value for itself. In an ecosystem, however, different actors' pursuits of their intrinsic values are inevitably intertwined due to the interdependencies of the actors. Therefore, each actor, while realizing the innovation's intrinsic value for itself, may also realize the innovation's extrinsic value for other actors. The literature has revealed at least two tasks for value realization: co-creating and appropriating.

On one hand, value is co-created jointly by the actors in an ecosystem. Much has been studied on how actors co-create value by developing complementary products or services (Ceccagnoli et al. 2012; Vargo and Akaka 2012). For example, an enterprise resource planning (ERP) vendor's multiple partners around the world customized and implemented the vendor's core software for the diverse needs of their customers (Wareham et al. 2014). Increasingly ecosystem research examines the co-creation by innovation producers and adopters. For example, in the ecosystem for a Swedish audiobook subscription service, Storytel employed social media to help customers learn to use the service, co-creating customer experiences (Suseno et al. 2018).

A variety of digital technologies support the co-creating task. For example,

The ERP vendor's web portal "identifies several hundred websites that are independently maintained and intended for use by partners and customers. These provide such services as discussion forums, blogs, white papers, listings of partner solutions (with comments and ratings), job listings, events listings, downloads, code samples, bug reports, tutorials, and advice. In this forum, end users can share best practices in areas such as partner selection, implementation processes, and total cost of ownership minimization" (Wareham et al. 2014, p. 1205).

With their memory and communication functions, digital technologies such as web portals and discussion forums help boost an ecosystem's information capacity. Through their interactions, the actors in the ecosystem realize the innovation's intrinsic and extrinsic values with the
information supplied by these technologies. For example, leads from web portals about potential partners (Wareham et al. 2014) and product usage tips shared in social media (Suseno et al. 2018) were information in the adaptation view, useful for an actor to co-create value with others.

On the other hand, the value co-created must be appropriated among the actors in an ecosystem. Sometimes value is appropriated explicitly. For example, in its iOS product ecosystem, Apple applied 30% cut on all app sales, in-app purchases, and subscription services (Ghazawneh and Henfridsson 2011). Such explicit value appropriation is implemented by online transaction processing (OLTP) systems and/or ledger technologies such as blockchain (Giraldo-Mora et al. 2019) with functions of sensing and tracing transactions. At other times, value is appropriated implicitly, even without the consent of the actors who created the value. Such implicit appropriation is present when the actors imitate each other in the ecosystem. For example, in the ecosystems for Mozilla's Firefox and Apple's App Store, developers often copied the designs and features of the products made by other developers (Song et al. 2017; Wang et al. 2018). A special case of this imitation is "coring," where ecosystem sponsors incorporated the functionality of complementary products into the core product or platform (Bender and Gronau 2017; Bender et al. 2019). For example, the sponsors of Firefox and Chrome, Mozilla and Google, respectively, both included popular features of their web browsers' extensions, made by third-party developers, in the core functions of their own browsers (Bender et al. 2019). In the interactions between an ecosystem sponsor and third-party developers, the latter's work is usually transparent to the former, making coring effortless (Bender et al. 2019). Even for opaque interactions, such as those among competing third-party developers, it is not too difficult to copy features using digital technologies' programming and sensing functions (Wang et al. 2018).

Whether value appropriation is explicit or implicit, digital technologies can help reduce
the uncertainties in the value realization process by supplying information about other actors’ actions. Where value is appropriated explicitly with OLTP or blockchain, the focal actor is well informed of other actors’ shares of the value they co-create. Where value is appropriated implicitly such as through imitation, the focal actor may be able to predict other actors' moves based on the replicability of its digital offerings and adapt accordingly, e.g., reinforcing intellectual rights protection or fortifying downstream capabilities (Ceccagnoli et al. 2012). In this way, information in the adaptation view is created as value is appropriated in an ecosystem.

In sum, two tasks of value realization (co-creating and appropriating) have been identified that the actors' performances rely on. Digital technologies can help inform the actors co-creating value with information about their partners and products, and the actors appropriating value with information about each other's actions. Therefore, responding partially to SRQ2 about the actors' performances,

**Proposition 2:** In a digital innovation ecosystem, an actor's performance depends on the value it realizes from the innovation through co-creating and appropriating value with other actors. Digital technologies support co-creating with their communication and memory functions, and appropriating with their programming and sensing functions.

Having discussed the actors' performances, I now explore how their performances may affect an ecosystem's overall performance. The ecosystem literature suggests that this upward shaping may follow direct and indirect ways. On one hand, an ecosystem’s overall performance may be derived directly from the performances of actors in the ecosystem. As a collective construct, an ecosystem's performance may be defined as the degree to which the values of the focal innovation are realized by the actors in the ecosystem. In fact, different actors may value different goals, and, even if they share the same goal, actors vary in the degree to which they
achieve the goal. Therefore, ecosystem performance is likely a "configural" construct that emerges in the form of a distinct pattern of the actors' performances through their bottom-up interactions called "compilation" (Burton-Jones and Gallivan 2007; Klein and Kozlowski 2000).

I suspect that compilation is yet another task of part-whole integration. As a configural construct, an ecosystem's performance is more meaningful than the sum or average of the performances of the actors in the ecosystem. Ecosystem-wide performance not only represents the different values pursued by the participants and the different patterns of their pursuits, but also reflects certain common values shared by the participants. For example, in two ecosystems for enterprise software, the sponsors promised and the complementors favored values such as fair cooperation, mutual success, and quality (Huber et al. 2017). The dearth of research on overall ecosystem performance calls for more studies to examine compilation by which ecosystem performance emerges from the actors' performances. Due to the senseable, memorizable, and traceable nature of digital artifacts, digital technologies have the potential to provide granular performance data, which can then be compiled to develop configural measures of ecosystem performance. Hence, responding partially to SRQ2 about ecosystem performance,

**Proposition 3:** The overall performance of a digital innovation ecosystem can be integrated through compilation of the performances of the actors in the ecosystem. Digital technologies support compilation by sensing, memorizing, and tracing actors' performances.

On the other hand, the performances of actors may shape their ecosystem's overall performance indirectly. Based on its own performance, an actor may adapt its engagement with the innovation and its adapted innovation activities may in turn change the innovation as a whole and the overall ecosystem performance. It has been found that actors undertake at least three

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8 The compilation task is not shown in Figure 2 due to the lack of empirical evidence thus far.
tasks of adaptation – searching, experimenting, and updating. In "searching," to improve their performances, actors look for new opportunities and solutions to existing problems. For example, mobile app developers monitored the performance of other developers in other product categories to search for opportunities there (Zhao and Davis 2017). More proactively, small and medium-sized enterprises (SME) attended the events organized by Working Together, an SME association, to look for business opportunities (Giudici et al. 2018). The meeting appointments for the events organized by the SME association and the so-called "success stories" of other app developers reported in the news, both carrying information representing opportunities to the observing actor, were made possible by digital technologies that help trace, sense, and memorize the information.

While searching, actors in ecosystems may also be "experimenting," the second adaptation task found in the analysis. Digital technologies have made it possible to conduct experiments online such as A/B testing (Kohavi et al. 2020). Actors employed digital technologies to experiment in many ways in ecosystems. In Apple's App Store, some developers released a series of updates of the same app over time to test market responses, following so-called "sequential experimentation" strategy (Davis et al. 2014). Others, however, executed "parallel experimentation" strategy and released multiple apps simultaneously (Davis et al. 2014). In both cases, digital technologies made it easy to set up the experiments with programmable software on one hand, and help collect experiment results (traceable usage data) on the other. In this way predictive models can be built to represent how customers (and competitors) would respond to these experiments. When the validated models, as information in the representation view, are applied to new product development or consumption, the information is then converted to the adaptation view to support the development or consumption.
The third adaptation task is "updating." For example, third-party developers had to update their apps to make them compatible with any new version of the Firefox browser Mozilla released (Luo et al. 2019). To ease such coordination, Mozilla regularized and shortened the update schedule of Firefox. As Mozilla's APIs helped app developers make compatible apps, there was a wiki system where Mozilla and app developers discussed the changes they made. From these interactions, information is created to reduce the uncertainty about product updates.

Summarizing, responding partially to SRQ2 about ecosystem performance,

**Proposition 4:** The overall performance of a digital innovation ecosystem can be derived indirectly from actors' adaptation, through searching, experimenting, and updating. Digital technologies support searching with their sensing and memory functions, experimenting with their programming and tracing functions, and updating primarily with their programming function.

Having discussed the effects of actors' performances on an ecosystem's overall performance, I now address the other side of SRQ2, regarding how an ecosystem as a whole affects actors' performances. The analysis has found two tasks that an ecosystem performs to moderate actors' value realization and adaptation, both critical to their performances. The first moderation task is "controlling." Autonomous actors may bring much creativity to the ecosystem, but autonomy without control may lead to poor quality and opportunistic behavior (Cennamo and Santaló 2019). To mitigate the downside of autonomy, mechanisms have been put in place to control the input and process of digital innovation ecosystems. For example, Mozilla employed a four-stage process to screen Firefox extensions contributed by third-party developers; only high-quality and interoperable extensions were admitted into the Firefox ecosystem (Tiwana 2015a). This input control mechanism might have protected the ecosystem's
overall performance and the value realized by some actors (e.g., users), but when the screening took a long time, the value realized by other actors (e.g., extension developers) diminished (Song et al. 2018). In addition to input control, ecosystems may control the processes by which actors interact with each other. For example, some ecosystems utilized blockchain to codify the rules for transactions in smart contracts, execute the rules automatically, and record the transactions in distributed and immutable ledgers (Schmeiss et al. 2019). The distributed nature of blockchain allows these ecosystems to control their processes without a central authority. Further, with the digital ledger as a single memory of immutable truth, these ecosystems can potentially eliminate opportunistic behaviors that would otherwise undermine the performances of the ecosystem and any actor in it.

The second moderation task is "promoting," referring to the efforts to make people aware of certain products or services in an ecosystem. For example, Sony PlayStation and Microsoft Xbox selectively endorsed video games for their 7th-generation consoles under the "Platinum: The Best of PlayStation" and "Xbox Classics" labels, respectively (Rietveld et al. 2019). As another example, in its ecosystem, an enterprise software vendor cross-sold with its partners by bundling or co-branding their products and certifying its partners' offerings (Schreieck et al. 2017). These promotion activities relied on various digital technologies. For example, Sony and Microsoft selected video games to endorse based on their sales and critics' ratings, information traced possibly by the online transactional processing (OLTP) systems and digitally archived trade press, respectively (Rietveld et al. 2019). Cross-selling of enterprise software was made possible by the cloud computing technologies that connected the software modules and the vendor's APIs and software development kits (SDKs) that offered detailed guidance on such connections (Schreieck et al. 2017). These technologies help produce models to explain and
predict the effectiveness of promotions, useful information in both the representation and adaptation views.

Taken together, an ecosystem's controlling and promoting shape actors' performances by moderating their value realization and adaptation. Screening as a form of input control determines access to the ecosystem (who are allowed to co-create value), and process control enforces the details and rules of value co-creation and appropriation. The ecosystem sponsor's promotion of certain products may prompt the participants to adapt their offerings in other ways that please the sponsor. Therefore, responding to SRQ2 regarding the effect of ecosystem performance on actors' performances,

**Proposition 5:** A digital innovation ecosystem can moderate the value realization and adaptation of actors in the ecosystem by controlling and promoting. Digital technologies support this moderation primarily with their programming and memory functions.

In summary, within a digital innovation ecosystem, as the actors innovate with digital technologies, their innovations are integrated into an innovation of varying structures at the ecosystem level. Meanwhile, the performances of the ecosystem and the actors in it are interdependent. Figure 3 presents this digital innovation process at both the actor and ecosystem levels, juxtaposing integration, value realization, adaptation, and moderation in a process model. This information view of digital innovation ecosystems would be incomplete if it were used to examine only the interactions within an ecosystem without explaining how different ecosystems interact. To see the forest for the trees, one may combine the information lens with the ecology lens.

**COMBINING LENSES: INFORMATION ECOLOGY THEORY**

Regarding the interactions among ecosystems, the focus of SRQ3 and SRQ4, the
ecological perspective presents different types of ecosystems at different levels of analysis, with lower-level ecosystems constituting higher-level ecosystems (Figure 1). The information perspective posits that the complexity, interdependencies, and uncertainty arising from the inter-ecosystemic interactions can be addressed by relevant information, created as the information needs are matched with information capacity. Now the ecological and information perspectives can be synthesized to address the remaining SRQs about the structure and function of digital innovations across ecosystems, using Figure 4 as a preview and guide.

Regarding innovation structure, SRQ3 focuses on the emergence of an innovation in a higher-level ecosystem from innovations in lower-level ecosystems. Like the emergence of an innovation within an ecosystem from the interactions and tasks of actors, the emergence of innovations across ecosystems is also an integration process in which tasks such as sharing, combining, and standardizing (Figure 2) may still be useful. Yet another integration task has been found from the ecosystem literature, "multi-homing," undertaken only across ecosystems. Multi-homing originally refers to an actor's strategy to join more than one ecosystem (Armstrong and Wright 2007). An oft-mentioned example of multi-homing is that a complementary product provider participates in multiple ecosystems, such as a mobile app developer joining both

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Figure 4. Interactions and Innovation Tasks across Digital Innovation Ecosystems

![Figure 4 Diagram]

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Apple's iOS and Google's Android ecosystems (Kang et al. 2019; Venkataraman et al. 2019). In addition, ecosystem sponsors can multi-home by orchestrating multiple ecosystems. For example, Alibaba connected the multiple ecosystems (for e-commerce and financial services) that the firm led (Jacobides 2019). Too, user organizations and consumers can multi-home by adopting and buying innovations from multiple sellers (Zhu and lansiti 2019). These multi-homing strategies rely on a variety of digital technologies: Data analytics for tracing and associating customer transactional data across ecosystems (Jacobides 2019), cross-platform programming tools for the developers making apps interoperable for different ecosystems (Kang et al. 2019), and enterprise application integration (EAI) for user organizations to link applications and systems purchased from different vendors’ product ecosystems (Rolland et al. 2018). Regardless of the specific scenarios and technologies employed, multiple ecosystems are connected by digital technologies so that relevant information can be created and distributed to the multiple “homes” of a focal actor, intentionally or inadvertently performing the integration tasks such as sharing, combining, and standardizing. For example, when Alibaba shared its customer data between its e-commerce and financial services ecosystems, predictive models of customer behaviors (as information in the representation view) can be built from traceable transactions with analytics tools. These models (as information in the adaptation view) can then guide the design and refinement of Alibaba's business model that combines the e-commerce and financial services capabilities available in the respective product ecosystems. In this way, Alibaba's innovative business model (along with its business ecosystem) emerged from the innovations in its product ecosystems (Jacobides 2019). Hence, responding partially to SRQ3, 

**Proposition 6:** A digital innovation in a higher-level ecosystem emerges from lower-level ecosystems through integration tasks such as sharing, combining, standardizing, and multi-
homing. Digital technologies support integration with their programming and tracing functions.

Regarding the function of digital innovations, SRQ4 pertains to the interdependence of ecosystem performances at different levels. On one hand, ecosystems at lower levels set possibilities for ecosystems at higher levels. Like the performance of a lower-level ecosystem, the performance of a high-level ecosystem is also a configural construct, derived from the compilation of how the components of the ecosystem perform. For example, the performance of Amazon's business ecosystem apparently depends on the performances of Amazon's product ecosystems for e-commerce and cloud computing. Moving to an even higher level, in the category ecosystem for enterprise resource planning (ERP), for example, the ecosystem's performance hinges on the quality of the ecosystem's learning that integrated the experiences, observations, and insights on realizing value from ERP expressed by vendors, adopters, and analysts working in their respective ecosystems at lower levels (Wang and Ramiller 2009). A critical part of this integration is the sharing of knowledge among the actors in lower-level ecosystems, not just in the online community for one vendor's product ecosystem (Huang et al. 2018), but also in public forums that span across product and business ecosystems.

Accordingly, this integration of performances (e.g., compilation and knowledge sharing) between ecosystem levels relies on information exchange through the actors' discourse. Despite the different scales of the ecosystems, information travels across levels via discourse vehicles (e.g., meetings, conferences, books, blogs, and tweets, etc.), many of which are digital or digitally-enhanced. Such information flowing across levels may be exemplified by the so-called "success stories" of certain actors developing or adopting an innovation. As information in the representation view, these success stories represent quasi-theories that connect a focal innovation to certain desired outcomes for both the stories' protagonists and the whole market category.
(Strang and Macy 2001). Hence, success stories are also information in the adaptation view as the generalized successes often inspire others to imitate the protagonists in such stories (Strang and Macy 2001). Digital technologies such as social media and digital archives can increase the reach ("going viral") and shelf life ("making it sticky") of success stories with communicable blogs and tweets and memorizable hashtags, for example. Therefore, addressing partially SRQ4,

**Proposition 7:** The performance of a digital innovation ecosystem at a higher level is integrated from the performances of constituent ecosystems at a lower level through discourse, supported by the communication and memory functions of digital technologies.

On the other hand, innovations as holons at higher levels set probabilities for innovations at lower levels. For example, in each ecosystem for a product, service, or technology category actors often develop an "organizing vision" for applying the product, service, or technological innovation (Swanson and Ramiller 1997). As a set of ideas about what an innovation is, what it is good for, and how to do it, an organizing vision helps actors interpret and legitimize the innovation and mobilize resources to realize the value of the innovation in their own specific organizations or ecosystems (Swanson and Ramiller 2004). Essentially, an organizing vision is the innovation at the category ecosystem level. The functions of the vision to interpret, legitimate, and mobilize the innovation may be fulfilled to a varying degree of effectiveness, leading to the differentiated performances of the category ecosystems. Regardless of its effectiveness, every organizing vision conveys information that represent the innovation's realities abstracted from specific organizations or ecosystems. Some actors and their offerings are included in the category while others are screened out. The innovation is promoted as an effective solution to an important problem (Abrahamson and Fairchild 1999) and certain techniques are promoted as "best practices" (Swan et al. 1999). These top-down controlling and
promoting activities moderate the performances of the lower-level ecosystems that constitute the category ecosystem. Too, this moderation across ecosystem levels relies on discourse. This is why industry analysts such as those from Gartner and Forrester remain influential gatekeepers who patrol the boundaries of category ecosystems with their research reports and events (Pollock and Williams 2016). The trade press, now digitally archived, is also an essential vehicle for such discursive moderation (Wang and Ramiller 2009). Therefore, addressing partially SRQ4,

**Proposition 8:** A digital innovation and its ecosystem at a higher level moderate the performances of constituent, lower-level ecosystems through discursive controlling and promoting, supported by the communication and memory functions of digital technologies.

In sum, Figure 4 illustrates the interactions of ecosystems across levels. At Level N in the middle, an ecosystem is a part of a broader ecosystem above at Level N+1. The value realization and adaptation of the ecosystem at Level N interact with those of the broader ecosystem above at Level N+1 through integration and moderation, as described by Propositions 6-8. Meanwhile, as a whole, the ecosystem at Level N, consists of and interacts with ecosystems or actors below at Level N-1. The levels in the figure are relative. For example, ecosystems at level N may be product ecosystems, business ecosystems, or category ecosystems. By combining the ecology and information lenses, I have sketched an information ecology theory of digital innovation ecosystems.⁹ The implications of this theory to digital innovation research are discussed next.

**DISCUSSION: ADVANCING DIGITAL INNOVATION RESEARCH**

Innovations today are no longer confined within organizational boundaries (Baldwin

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⁹ This theory shares lineage with the interdisciplinary field of information ecology, where scholars employ ecological metaphors to stimulate the analysis of the information environments for IT design (Nardi and O’Day 1999), organizational information management (Davenport and Prusak 1997), government services (Bekkers and Homburg 2005), and science policies (Eddy et al. 2014). Expanding from the usual focus of information ecology research on information problems in local settings, the theory developed here may be applied to a wide range of information environments from intra-organizational ecosystems to global business and technology landscapes.
A digital innovation, due to its layered modular architecture, often involves many autonomous actors who apply their resources to a common set of problems in a loosely-coupled ecosystem. In these digital innovation ecosystems, although autonomy may spawn much creativity, the elevated complexity, interdependencies, and uncertainties would be challenging to manage, especially to integrate the efforts of various parties into a coherent whole. Applying ecology and information ideas, I have developed a theory that explains digital innovation as a multilevel process of meeting information needs in and across ecosystems. This information ecology theory has the potential to advance digital innovation research in three directions: part-whole relations, role of digital technology in innovation, and multilevel analysis.

The Shift from the Parts to Part-Whole Relations

With the concept of holon, the information ecology theory helps shift the focus from the parts of a digital innovation ecosystem to part-whole relations. The literature review above shows that most studies of digital innovations in ecosystems tended to focus on the parts (e.g., the actors, their actions, and the product or service components they make or use). The innovation or ecosystem as a whole (e.g., products or services as a package or a collection of actors interacting with each other) has been left largely in the background. This imbalance is probably due to the emphasis on the division of labor implied in modular designs and the difficulty observing and thus conceptualizing an ecosystem as a whole. Nonetheless, as Propositions 1, 3, and 5 (Figure 3) suggest, the parts and the whole interact with significant consequences on both sides. Regarding the integration of the actors' activities into an innovation as a whole package, sharing, combining, standardizing, and multi-homing have been identified as the tasks for such integration. Less clear, though, is compilation, the integration of the actors' activities

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10 In Gregor’s (2006) taxonomy of theories in IS research, the information ecology theory developed here may be a Type II theory that “provides explanations but does not aim to predict with any precision” (p. 620).
performed into the ecosystem's performance. Although a value-based definition of ecosystem performance has been presented here, other conceptions of ecosystem performance exist, such as productivity, robustness (Iansiti and Richards 2006), resilience (Tiwana 2013), etc. For each conception, how to compile ecosystem performance from actors' performances is still open for debate and further research.

Regarding the moderation of the parts by the whole, a promising stream of IS research focuses on ecosystem governance and examines the input and process controls that ecosystem sponsors exert on other participants (Foerderer et al. 2019; Huber et al. 2017; Tiwana et al. 2010; Wareham et al. 2014). However, given the loosely-coupled nature of ecosystems and the autonomy of the participants, the authority required for such governance measures is not always clear or unchallenged. For example, governance would have few teeth in a category ecosystem since nobody owns the category (Wang and Swanson 2007). Therefore, more research is needed to identify other ways of part-whole moderation such as the distributed control with smart contracts without a central authority (Schmeiss et al. 2019).

For instance, a recent study of part-whole relations in a digital innovation ecosystem found that a game console's innovation generativity (measured by the diversity of games produced by third-party developers for the console) had a positive effect on each game's quality (measured by customer satisfaction with the game), but that effect declined as the ecosystem matured (Cennamo and Santaló 2019). While this finding illustrates the moderation of the parts by the whole (P5 in Figure 3), the reason behind the result can also indicate how the parts affect the whole. As the authors speculated, high-quality games (called "superstars") in a console's ecosystem might have raised the reputation of the whole ecosystem, benefiting the sales of all games for the console. Such "reputation spillover effect" not only illustrates the integration task
(P1 in Figure 3) but might have caused free-riding of low-quality game developers as a form adaptation (P4 in Figure 3). However, the reputation of the console's ecosystem as a performance indicator was only implied but not measured in the study. Although it may be tempting to tally up the performances (e.g., customer satisfaction) of all games in the ecosystem, reputation spillover suggests that only the superstars’ performances would matter. In short, these part-whole interactions as explained by the information ecology theory were critical to the performance of the game-console ecosystem. Direct measurement of ecosystem performance would both strengthen the authors' argument and help game developers and console makers innovate.

The Role of Digital Technology in Digital Innovation Ecosystems

The information ecology theory expands the understanding of the role that digital technologies play in managing digital innovations in ecosystems. In contrast to the view that IT can provide only formal or internal information (Galbraith 1974; Simon 1973), the above analysis of the ecosystem literature shows that a variety of digital technologies can increase the ecosystem's capacity to provide multiple types of information to support a variety of interactions and innovation tasks. Digital technologies can not only enable the division of labor (e.g., Lee and Berente 2012), as portrayed by the paradox at the onset of the paper, but also facilitate the integration of efforts in an ecosystem (P1 in Figure 3 and P6 in Figure 4). Table 3 summarizes the functions of digital technologies, corresponding to the samples of the information provided by these technologies and needed to support the interactions and innovation tasks.

<table>
<thead>
<tr>
<th>DT Function</th>
<th>Sample DT</th>
<th>Information Example</th>
<th>Part/Whole Interaction</th>
<th>Innovation Task</th>
<th>Related IS Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programming</td>
<td>Software code &amp; API</td>
<td>Product architecture</td>
<td>Combining code to create product</td>
<td>Combining</td>
<td>Robotics/AI</td>
</tr>
<tr>
<td>Sensing</td>
<td>Online review system</td>
<td>Market demand</td>
<td>Listening to customers</td>
<td>Searching</td>
<td>Internet of Things (IoT)</td>
</tr>
<tr>
<td>Communication</td>
<td>Social media &amp; online community</td>
<td>Usage tips</td>
<td>Enhancing user experience</td>
<td>Co-creating</td>
<td>Knowledge collaboration</td>
</tr>
</tbody>
</table>
First, *programming* refers to the function of technologies such as software code and APIs to make an object perform certain actions by following a set of instructions. Programmable objects may be combined by software to generate an innovative product, as well as information such as the product architecture. Programmable objects may also be edited and the information updated in this process. Hence, the programming function is crucial to the interactions for some of the integration and adaptation tasks in the ecosystem.

*Sensing*, the second function, supports innovation tasks such as searching. Thirdly, the *communication* function of digital technologies is self-explanatory, supporting the coordination of actors in their interactions for several innovation tasks. This function also refers to the communication among digital artifacts so they can be linked to support innovation tasks. The fourth function, *memory*, represents a digital technology's ability to document and archive information, important to any innovation task that needs a memory (e.g., sharing for integration, updating for adaptation, and controlling for moderation). *Tracing*, the fifth function, utilizes digital trace data to "chronologically interrelate events and entities over time" (Yoo 2010, p. 231). This function proved to be essential, for example, to Alibaba's orchestration of multiple ecosystems (Jacobides 2019). Lastly, the function of *association* allows entities to be related to each other according to certain common attributes. Obviously, this function is useful to the promoting task for part-whole moderation in an ecosystem.

These functions may be performed jointly. For example, a recommender system serving the association function may rely on trace data sensed from the memory of certain
communication media. Finally, the above description of the functions that digital technologies serve in supporting the innovation tasks and interactions is by no means exhaustive. Future research can seek to discover other functions of digital technologies for supporting the innovation tasks and interactions that have been discussed here, and possibly other tasks and interactions. For example, although not reported in the articles about ecosystems in the collection for this study, "data exhaust" or "digital exhaust" (data generated as a by-product of users' online activities) has been reused to continuously refine and improve products and processes (Terwiesch 2019; Zuboff 2019).\(^{11}\) This "reusability" function of digital technologies apparently can support the innovation task "updating" for "adaptation." Equally interesting would be the exploration of how some digital technologies might hinder or constrain certain innovation tasks and interactions.\(^{12}\)

Notably, investing in digital technologies with the above functions does not guarantee a thriving digital innovation ecosystem. Sahaym et al. (2007) found that IT investment led to loosely coupled organizational forms only when industry standards existed. Industry standards, as the authors suspected, might have lowered asset specificity and thus increased the feasibility of a firm working with contingent workers and other autonomous actors (just as in an ecosystem). Rather than treat standards and asset specificity as exogenous factors, the information ecology theory developed here, with its emphasis on the functions of IT, raises the possibility that certain functions of IT may directly facilitate the development of industry standards (e.g., communication and memory supporting standardizing tasks in ecosystems) and reduction of asset specificity (e.g., programming supporting decoupling and recoupling of

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\(^{11}\) I thank the associate editor for suggesting the use of this example.  
\(^{12}\) For example, previous investments in certain technologies may limit the options that an actor can take presently (Rolland et al. 2018; Woodard et al. 2013).
information and physical objects). Hence, the view of standards and asset specificity as endogenous factors implies that, when firms make boundary decisions, what matters may not be how much they invest in IT, but rather which IT with what functions to acquire.

**Multilevel Analysis of Digital Innovation Ecosystems**

With its roots in ecology, the information ecology theory can inspire multilevel studies of digital innovations. On one hand, digital innovation is a multilevel phenomenon as digital technologies can enable innovations at process, product, business, category, or even higher levels. Accordingly, ecosystems may form to manage digital innovations at different levels. On the other hand, as the concepts of holon and holarchy remind us, every ecosystem is a holon and every subordinate or superordinate of an ecosystem is also a holon, being both a part and a whole at the same time. Taken together, therefore, the multilevel nature of digital innovation ecosystems renders single-level analysis (although still useful and informative) inadequate. But how can we meet the challenges of conducting multilevel studies of digital innovations?

A modest step forward would be to study digital innovations at another level, off the beaten path. As the above literature review shows, most studies of ecosystems focused on the intra-ecosystemic dynamics at the product or business level. Relatively little research has been conducted on ecosystems within a firm, at the category level, or even higher. For example, by studying the evolution of a digital innovation as a technology category, we may be able to better understand the "best practices," "industry norms," and "institutional logics" that often inform innovations at the product or business level. The findings from single-level studies at different levels, including those at underexplored levels, can prepare us for truly multilevel studies.

A truly multilevel study would examine digital innovations at two or more levels. For example, how does a business ecosystem emerge and evolve from its underlying product
ecosystems? How is information being shared and/or blocked among the actors belonging to the same business ecosystem but not the same product ecosystem? What role do digital technologies play in such information sharing and/or blocking? Another example of multilevel analysis is to study cross-level interactions. For instance, a longitudinal study of knowledge sharing in the ERP category ecosystem found that software vendors, consultants, and adopters contributed local knowledge from the business level to the broader ecosystem (Wang and Ramiller 2009). However, the other side of this cross-level learning cycle, i.e., how the ecosystem fed important lessons learned back to the participating businesses, was only speculated without empirical data in that study. This gap can be filled by examining knowledge sharing within ERP vendors' business ecosystems, especially whether and how participants reference external, ecosystem-level knowledge. This kind of extension would help put together a complete picture of the cross-level learning cycle between organizational learning within business ecosystems and community learning at the category ecosystem level. Further, understanding of this cross-level interaction may help enrich our knowledge of digital innovation at each level. For example, a recent study of knowledge sharing in an online community in SAP's business ecosystem found that SAP's efforts to seed content in the community prompted other members' contributions (Huang et al. 2018). This finding could be refined if we knew which member contributions had been truly original and which had been cycled back from public discussions about the product in the ERP category ecosystem. Identifying truly original contributions would help not only improve the precision of SAP's calculation of the return on its knowledge-seeding investment, but also contextualize this investment in a holistic portfolio of knowledge collaboration strategies within and beyond SAP's business ecosystem.

In sum, the information ecology theory I have sketched here affords opportunities for
digital innovation research to connect the parts with the whole of an ecosystem, theorize the role of digital technologies in such connections, and explore cross-level or multilevel interactions. Pursuing these opportunities may even lead us to the Information Systems of the future.

**CONCLUSION: INFORMATION SYSTEMS OF THE FUTURE**

Nearly three decades ago when Lucas and Baroudi (1994) discussed the role of IT in designing organizations, they predicted that "the organization of the future may not be an organization at all" (p. 22). They imagined a future in which new organizational forms, strikingly different from conventional organizations, would be made possible by modern IT. One of such forms they mentioned was "an amalgamation of independent agents" (p. 16). Echoing their prediction, digital technologies have made ecosystems possible today as a new organizational form to develop and implement innovations (Yoo et al. 2010). With their layered modular architecture, digital technologies enable the division of labor among numerous autonomous actors. While the actors bring almost unlimited creativity to the ecosystem, they also add complexity, interdependencies, and uncertainties that escalate the need for information. Traditionally, information systems have facilitated and shaped the interactions among actors within organizations (Swanson 2007). As organizations of the future, ecosystems, with their escalated information need, rely on information systems even more. The information ecology theory outlined here posits that a variety of digital technologies perform multiple functions to provide relevant information, which supports interactions and tasks in ecosystems of varying scales, crossing the boundaries of conventional organizations. In this sense, such trans-organizational information infrastructures (Winter et al. 2014) exemplify the IS of the future.

As the last column of Table 3 illustrates, to build an effective IS for a digital innovation ecosystem, many streams of IS research beyond the digital innovation focus, can shed light. For
example, the advancement of artificial intelligence (AI) and robotics has given the word "autonomy" a new meaning. Autonomous actors in an ecosystem are not only humans and organizations not bound by employment-based authority, but also autonomous agents/robots operating independently without interferences from their owners. The programming function of autonomous agents allow them to join the interactions with human actors and other machines (Swanson 2020), making the combining task for innovation even more complex and unpredictable. For instance, information is traditionally created first to represent reality (information in the representation view) and then used for decision making (information in the adaptation view). With the programming function embedded in the autonomous agents, the information ontology is reserved as the digital reality is created first (information in the adaptation view) and then represented in some physical form later (information in the representation view) (Baskerville et al. 2020). What information is needed and when is it needed to shape the interactions involving autonomous agents in a digital innovation ecosystem?

Not just IS scholars studying AI or robotics can apply and extend their knowledge in the multilevel context of digital innovation ecosystems. For example, do wide adoption of the Internet of Things and proliferation of sensor data make the sensing function and searching task easier or harder to perform? Do the theories of knowledge collaboration in open online communities such as Stack Exchange still apply to knowledge sharing and value co-creation in managed or exclusive ecosystems? In developing open source software in an ecosystem, what information about the ecosystem as a whole is critical to project success? As digital analytics tools trace and associate sensitive personal data in and across ecosystems, how privacy and security can be protected in order to innovate responsibly?

All in all, this information ecology theory may help cultivate an ecosystem for IS
scholars, where we apply our diverse areas of expertise (in digital innovations or other topics) to a common set of problems and challenges in developing the information systems of the future.

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