What's in an Ecology? A Review of Artifact, Communicative, Device and Information Ecologies

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Decades of research have examined human-computer interaction with or across multiple (computational) artifacts as artifact ecologies, communicative ecologies, device ecologies, information ecologies, and other related conceptualisations. Although rich on observations and concepts, the works are largely self-contained and focused on using and developing concepts internally, with little ambitions toward synthesizing and strengthening what we know about these different theoretical concepts. In this paper we take stock of the literature on ecologies et al. in HCI and CSCW with the aim of identifying key positions, differences, similarities, and sub-concepts, as well as opportunities moving forward. From a reviewed corpus of 129 publications we consolidate 54 concepts into four influential positions and identify cross-cutting themes, conceptual gaps and challenges moving forward. In addition, we discuss issues related to the disconnected nature and theoretical quality of the concepts and how that impacts implicit theorising within our research community.

CCS Concepts: • **Human-centered computing** → **HCI theory, concepts and models**; **Interaction paradigms**.

Additional Key Words and Phrases: artifact ecologies, communicative ecologies, device ecologies, information ecologies, theory

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1 INTRODUCTION

Human-computer interaction is rarely about interacting with a single device or software in isolation. It entails switching between multiple devices and applications, and increasingly individual devices are, and can be understood as, interfaces to complexes or networks of software systems running on a myriad of different hardware configurations in data centers, or on devices within the local area network. Even more so, human-computer interaction happens in the context of other artifacts and resources within a particular environment. Across four decades, multiple works have adopted or developed different ecological theories and metaphors to try to make sense of, conceptualise and theorise on the above. The tone and focus in the early work from the 1980s and 90s, e.g. Capurro [28], Harris [52], Kling and Scacchi [73] and, Star and Ruhleder [123], is on bringing attention to the multiplicity of artifacts and ecological perspectives, arguing for more holistic and cultural dimensions and establishing a useful vocabulary. In parallel, several technological visions were proposed, with Weiser's [92] vision of the computer for the 21st century being the most prominent. This spawned significant interest in making ecologies an object of design, focusing on ubiquitous and context-aware computing, and later cross-device interaction and internet of things. As multiple devices, software applications and networked services have become more common, empirical work has taken these constellations as an object of study [e.g. 10, 67, 116].

Extensive work has been done to explore models and interaction techniques that support cross device interaction [e.g. 56, 57, 93] (see also Brudy et al.'s survey of cross-device interaction [27]).

When examining these efforts, a complex landscape of concepts and terms emerge, that span multiple understandings, theoretical underpinnings, foci, implications and approaches. Empirical, theoretical and design-oriented work has proposed personal artifact ecologies, technology assemblages, communicative ecologies, cultural ecologies, information ecologies, hybrid ecologies, cross device ecologies, ubiquitous computing ecologies, just to name a few (see tables 2, 3, 4, 5 for a complete list). Much of this work proposes and develops a specific concept but does little to connect with other work systematically. For instance, Rossitto et al.'s work on constellations of technologies [116] only briefly mentions other works on artifact ecologies [17]. Bødker et al.'s work on community artifact ecologies [20] expands on Jung et al.'s concept of personal artifact ecologies [67] , but refrains from discussing other concepts extensively. Tchounikine [128] discusses various definitions of ecologies of artifacts but makes distinction between instrumental clusters of artifacts, and collective work activities as two different approaches to such ecologies. Raptis et al.'s work on digital ecologies [110] is an attempt to integrate a subset of the concepts discussed in literature. Turner [133] discusses different perspectives on information and artifact ecologies to provide a broader understanding of everyday life with technology. Recent work of Brundy et al. [27] surveys multi-surface interaction, With a corpus that is larger than ours, they reflect on their terminology, similarly to what we set out to achieve with the current paper.

Our starting point is that the multiple perspectives and their parallel genealogies create a somewhat blurred image of how HCI conceptualizes, studies, and designs for collections of artifacts. Our thesis is that commonalities and differences across the proposed concepts need to be understood better for the benefit of the research community: Not only is it possible to cluster the existing works into fewer concepts without losing the explanatory strength and consistency across the body of work; cross-fertilization has the potential of enriching the concepts and invite new ways to study, theorize and design for ecologies of artifacts. Our contribution is threefold: First, we present a survey of the existing concepts and draw out important distinctions between different kinds of research and roles of theory. Secondly we synthesize concepts as to propose a simple clustering into four categories. Third, we then discuss these distinctions and how they might enrich the understanding across analytical levels, and crosscutting themes. The structure of the paper reflects this, following from our review method, and concludes with a discussion on the lack of connections and state of theorising.

2 REVIEW METHODOLOGY

The review approach follows the semi-systematic and integrative review approaches discussed by Snyder [121]. The reviewed literature was collected with departure in sources familiar to the authors, e.g. works on information ecologies [101], artifact ecologies [17, 67], communicative ecologies [45] and cross device research [56]. From there we expanded the corpus by (a) examining works that cite, or are cited-by, publications in the corpus, and (b) identifying concepts, e.g. technology assemblages or service ecologies in the expanding corpus, and searching for these on Google Scholar and the ACM Digital Library. This was done iteratively as the list of publications and concepts expanded. We have adopted an inclusive strategy insofar as we include relevant publications and perspectives cited in the key HCI/CSCW/UBICOMP-oriented conferences and journals to inform the genealogy of, and theoretical influences in, the survey[1]. The criteria used to determine whether to stop the recursive search were as follows: 1) does the paper clearly address technology (e.g. infrastructure, artifacts, devices)? 2) does the paper address technology in use (e.g. the interaction between the

[1] Four publications cited in the primary literature were unavailable to us at the time of writing and have been excluded from the survey.

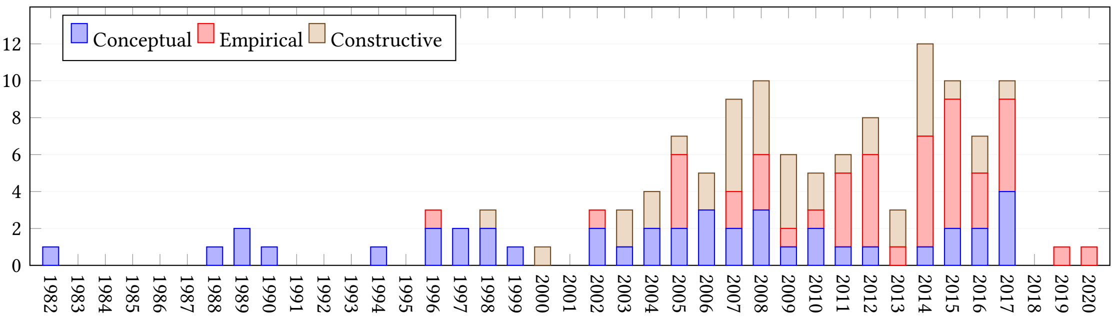

Fig. 1. Publications per year for each research type: Constructive-, empirical, and conceptual research (see section 3)

technology and people, or the utility/functionality of technology is discussed)? And 3) Is the focus of the paper relevant to the wider fields of HCI/CSCW/UBICOMP (e.g. we would ignore papers that focus heavily on knowledge management, human resources and management disciplines).

We have excluded papers that study or discuss application of technology within ecological research [e.g. 7, 69], works that apply ecological psychology [e.g. 47] in (interface) design [e.g. 51, 111, 139], or positions that discuss more generic perspectives within research (sub) areas such as smart environments, ambient intelligence, internet of things, etc. Further, we have chosen not to include thesis work as the identified theses are paper-based formats, hence the discussion in the theses mirror those in the included papers [e.g. 74, 75, 94]. We have included works that explicitly focus on, or discuss, an ecological perspective in the work, or works that build upon existing work within that definition. Several of the publications have been published outside the main HCI and CSCW venues and many intermediate discussions has happened in workshop contributions [e.g. 14, 58] and elsewhere [e.g. 141]. The final list includes 129 publications and 54 identified concepts. Since the first identified publication, Kling and Scacchi [73], 54 different concepts have been proposed and worked on in HCI and CSCW research. Figure 1 highlights the distribution of the work and an increased interest in the topic since the early 2000s.

3 ANALYSIS: RESEARCH TYPES AND THE ROLE OF THEORY

In the review we want to examine the conceptual and theoretical developments across the corpus. First, we examine the different types of research based on Oulasvirta and Hornbæk's [104] adoption of Laudan's discussion on different types of research problems and solutions. Second, we categorize the publications according to how (if) they apply the concepts and the role theory play in the work. Here we combine different perspective on the role of theory in HCI [e.g. 50, 68, 115] to try to make sense of the state of the concepts and of how theory is positioned in the works.

3.1 Research types

Categorizing the different genres of research allows us to identify the multiplicity of approaches informing the conceptual developments across the corpus and points to ways in which combinations of research types can further develop the concepts. Oulasvirta and Hornbæk present three categories of research types within HCI: *empirical research* that aims at creating or elaborating descriptions of real-world phenomena related to human use of computing; *conceptual research* that aims at explaining previously unconnected phenomena occurring in interaction; and *constructive research* that producing understanding about the construction of an interactive artefact for some purpose in human use of computing [104, p. 4958]. Further, they observe how HCI often mixes problem types, e.g. design work that takes inspiration from

Research types	Descriptive	Applied	Analysis	Synthesis
Empirical *29 publications*	[89, 101, 102, 109, 135, 145]	[9, 33, 38, 39, 48, 65, 90, 95, 118, 130, 136, 137]	[20, 21, 46, 66, 82, 97, 134, 138, 146]	[44, 63]
Empirical – Conceptual *25 publications*	[25, 64, 99, 123, 126]	[10, 54, 55, 62, 140]	[5, 12, 17, 19, 32, 70, 100, 103, 116, 119, 124, 149]	[22, 67, 73, 80]
Conceptual *22 publications*	[4, 24, 26, 52, 53, 58, 125, 127, 132]	[107]	[2, 18, 28, 77, 78, 128, 133, 144]	[16, 71, 76, 106, 131]
Conceptual – Constructive *12 publications*	[1, 43, 56, 93, 114]	[11, 45, 61, 120]	[88, 91]	[110]
Constructive *27 publications*	[3, 30, 83, 98, 112, 113, 143, 147]	[6, 15, 31, 40, 42, 49, 57, 60, 72, 79, 81, 85, 87, 122, 129, 142]	[34, 86, 108]	none
Constructive – Empirical *12 publications*	[8, 37]	[13, 29, 59, 117, 141, 148]	[35, 41, 96, 105]	none

Table 1. Corpus of 129 publications clustered by research types and the role of theory in the work.

theoretical concepts developed in or outside HCI; empirical evaluations of prototypes; applying a specific theoretical framing to analyze empirical data, etc. In applying these categorizations analytically, we extend them by making a distinction between work that uses elements of the other categories internally, e.g. evaluating a presented system or proposing concepts local to a specific empirical case, and work that makes an effort in moving from material developed within one category towards one of the other two. Table 1 illustrates the distribution of the work across the three research types and combinations. In line with what [104] found, a majority of the work is focusing purely on empirical and constructive research types, with some work focusing on the conceptual work alone. In terms of theoretical and conceptual development, theorizing from empirical work is far more common than theorizing from constructive work. Work that combines empirical and conceptual types often take inspiration in a concept either in framing the work or directing the empirical focus.

3.2 The role of theory and concepts

Contributions apply the ecological framing differently across the corpus. Identifying the different applications and the role theory plays in the publications allow us to pinpoint some of the key theoretical developments and identify cross-cutting concepts. We developed the four theoretical roles from observations across the corpus and with inspiration from [50, 68, 115]. When we use the word 'theory', we assume that at the highest level, the use of ecology or similar can be understood as a theory that frames and positions the work. The four roles theory plays in the corpus are: a *descriptive* role is when a theory is used to frame the work without further engagement with the theory or concepts; *application* of theory is when the role is to inform constructive and/or empirical work and the analysis thereof without engaging with the merits or qualities of the theory or concepts themselves; theoretical *analysis* involves engaging with the a particular theoretical framework with the goal of discussing its qualities and/or developing its inner concepts; and *synthesis* refers to work that compare and juxtapose multiple theories with the goal of integrating multiple concepts into a unified framework. The categories are intended to convey what the 'ecological' framing do for the work and how the individual publications engage with the theoretical framing. The two former use the theory 'as is', whereas the two latter take on a more generative perspective.

Of the 35 publications use their concept descriptively to position or frame the work, we see a large variation in this category, from work that mentions an ecological concept in passing [e.g. 89], relies on implicit or dictionary definitions [e.g. 83] and work that frames a particular empirical or technical focus [e.g. 64, 93, 145], to work that presents a concept in conjunction with other concepts [e.g. 24, 123] or discusses the concept without further development [e.g. 52, 99]. This category reflects the genealogy of the ecological concepts and the movement from acknowledging that various new framings are needed to using a concept to establish a familiar framing for empirical and constructive work. For instance, early works on *information ecology* [99, 101] discuss the concept, whereas the theoretical development happens later [100]. Similarly, technology-oriented work by Rekimoto [112] and later Houben et al. [56] uses this multi-computer and cross-device framing to discuss new research areas without a need for theoretical grounding.

44 of the publications apply different ecological concepts in an applied way, understandably as part of design and empirical analysis. For the empirical work, three perspectives can be observed: First, work that studies an ecology of technologies, e.g. calendars, personal belongings [38, 90]; second, work that examines activities within specific environments and contexts, e.g. hospital ward, meetings, design and learning environments [9, 95, 137, 140]; and third, technologies and use (and non-use [118]) within specific domains and/or activities [e.g. 29, 62, 65]. Similar divisions can be seen within the constructive work, e.g. challenges in designing for a specific kind of ecological concept [e.g. 57, 81, 129], or designing for a particular context [e.g. 49, 141], and use scenarios [e.g. 15, 122], and additionally discussion on the underlying technologies and software models [40, 60, 87, 120]. Common for this work is that the ecological concepts are used to frame and scope the object of study or design. Insights developed pertain to the (use) case study and technologies studied and designed.

38 of the publications engage with their ecological concept analytically, reflecting on and developing the concepts themselves. Several of the influential concepts (see section 4) originate in this work, e.g. *information ecologies* by Nardi and O'Day [100] or *communicative ecologies* by Altheide [2]. Several of the positions develop their concepts by applying 'ecology' as a metaphor from biology [e.g. 77, 100], through various applications of existing theories in CSCW/HCI, e.g. Activity Theory [17], Distributed Cognition [138] and semantics [77], or in developing on prior work included in this survey. Another common pattern is to develop the theoretical foundation more thoroughly and cite related concepts, e.g. Bødker et al. [20] considering Nardi and O'Day [100], Krippendorff [76] and Jung et al. [67] in developing their perspective. However, the theoretical and conceptual developments are still self-referential and internal to the works, resulting in concepts that converge on similar topics, concepts and analyses, e.g. Rossitto et al.'s [116] *constellations of technologies*, Sawyer et al.'s [119] *digital assemblages*, Jokela et al.'s [66] *device ecologies*, Bødker et al.'s [20] *community artifact ecologies*, without being thoroughly developed into a coherent theoretical framing. Similarly, constructive work shows a stronger conceptual commitment to designing and developing technologies from a given ecological perspective, e.g. analysing what *device ecologies* implies for the underlying software models and design rationale [34, 86].

Finally 12 of the published work go further and explicitly synthesize and/or develop new conceptual dimensions based on previous work. Here we see three different approaches: First, work that develops a full analytical framework. This is present in both the early contributions [22, 73, 76] and more recent work [16, 67, 71]; second, work that strive to integrate multiple perspectives from related work into useful models and concepts. Here, Jarrahi et al. [63] integrate multiple perspectives in their discussion of artifact ecologies and how different contexts shape the ecologies. Larsen-Ledet et al. [80] integrate work on artifact ecologies with Rossitto et al.'s [116] work on constellations of technologies and develop concepts for discussing transitions in and across ecologies; and third, work that survey existing work with the aim of integrating multiple elements into an analytical or conceptual model. In their short review Raptis et al. [110] discuss and integrate multiple concepts and propose *digital ecologies* as an overarching term. Treré and Mattoni [131] categorise four different ecological perspectives based on theory and work within media studies. While offering strong concepts grounded in theory and existing work within the corpus, this work is also underdeveloped from a

	Information Ecologies	
Primary	Harris [52] (1989); Capurro [28] (1990); Nardi and O'day [101] (1996); Hasenyager [53] (1996); Albrechtsen and Jacob [1] (1997); Nardi [99] (1998); Nardi and O'Day [100] (1999); Baker and Bowker [6] (2007); Finin, Joshi, Kolari, Java, Kale, and Karandikar [43] (2008); García-Marco [46] (2011); Treré [130] (2012); Johri, Teo, Lo, Dufour, and Schram [65] (2014); Vasiliou, Ioannou, and Zaphiris [136] (2014); Wang, Guo, Yang, Chen, and Zhang [144] (2017)	
Secondary	Cultural Ecologies	Bell [10] (2002); Wakkary and Evernden [141] (2005); Wakkary, Hatala, and Newby [142] (2006); Cook, Pachler, and Bachmair [33] (2011)
	Ecology	Turner [133] (2017)
	Socio-cultural Ecology	Pachler, Bachmair, and Cook [106] (2010)
	Hybrid Cultural Ecology	Lindtner, Nardi, Wang, Mainwaring, Jing, and Liang [82] (2008)
	Technologies of Literacy	Bruce and Hogan [26] (1998)
	Ecological Perspective	Zhao and Frank [149] (2003)
	Ecology of Ubiquitous Socio-technical Relations	Constantinides and Barrett [32] (2005)
	Teaching Learning Ecologies	Bailey and Barley [5] (2011)
	Ecology of Infrastructure	Star and Ruhleder [123] (1996)
	Web Ecologies	Chi, Pitkow, Mackinlay, Pirolli, Gossweiler, and Card [30] (1998)

Table 2. Primary publications use the Information Ecology terminology. Secondary concepts indicate work that is categorized as similar to Information Ecologies.

theoretical perspective, either by offering tentative and incomplete concepts or developing concepts that fit a particular case without considering broader applications.

4 SYNTHESIS OF INFLUENTIAL CONCEPTS

Here we provide a deeper introduction to four influential positions – *information ecologies, artifact ecologies, device ecologies, and communicative ecologies* – selected based on both a higher number of articles that use the concept, and a higher number of other concepts that refer to the influential position (either to differentiate or to build upon). Within these we group the other positions that are either directly related (they are introduced as an extension or in direct connection with existing either the dominant or other minor positions within the same group), or they are trying to achieve a similar goal. Common to all the positions is (1) an interest in relationships between different aspects of what is included in the ecology, and (2) an attempt to take a holistic perspective to understand the particular research context.

4.1 Information Ecologies

There are several concepts in which the characteristics of the physical location and the cultural context are core in the ecology, with the most influential (and thus headlining concept) being *information ecologies*. Information ecologies itself have had multiple strands of development, including Capurro [28], Nardi and O'Day [100] and Albrechtsen and Jacob [1]. As a concept the main development and definition we refer to is from Nardi and O'Day who define it as *"a system of people, practices, values, and technologies in a particular local environment. In information ecologies, the spotlight is not on technology, but on human activities that are served by technology"* [100].

Another strand of information ecology comes from Baker and Bowker [6], who build on Star and Ruhleder [123] and present the concept as *"inclusive of data sets and data collectors, information systems and knowledge makers, as well as digital federations and social networks"*[6, p.128]. Garcia-Marco brings these strands together stating *"what all these approaches suggest is that the way in which an evolved society manages knowledge transfer is very complex, with many subsystems and logics competing and collaborating, converging and diverging"* [46, p. 107]. This quote speaks to understanding being tied to some big picture of a phenomena, going beyond technological artifacts or activities to also include the physical space and cultural practices of a particular context. By placing everything within the scope of

	Artifact Ecologies	
Primary	Krippendorff [76] (1989); Krippendorff [77] (2006); Vyas and Dix [140] (2007); Jung, Stolterman, Ryan, Thompson, and Siegel [67] (2008); Krippendorff and Butter [78] (2008); Kirsh [71] (2010); Bødker and Klokmose [16] (2011); Bødker and Klokmose [17] (2012); Oleksik, Milic-Frayling, and Jones [103] (2012); Sørensen and Kjeldskov [122] (2014); Kjeldskov et al. [72] (2014); Dittmar and Dardar [38] (2014); Vasiliou, Ioannou, and Zaphiris [137] (2015); Bødker and Klokmose [18] (2015); Bødker, Korsgaard, and Saad-Sulonen [20] (2016); Bødker, Korsgaard, Lyle, and Saad-Sulonen [19] (2016); Erkut and Serafin [42] (2016); Bødker, Lyle, and Saad-Sulonen [21] (2017); Jarrahi, Nelson, and Thomson [63] (2017); Vasiliou, Ioannou, Stylianou-Georgiou, and Zaphiris [135] (2017); Tchounikine [128] (2017); Vasiliou, Ioannou, and Zaphiris [138] (2019); Larsen-Ledet, Korsgaard, and Bødker [80] (2020)	
Secondary	Clusters of Artifacts	Bertelsen and Bødker [12] (2002)
	Technological Assemblies	Hindmarsh, Heath, vom Lehn, and Cleverly [54] (2002); Hindmarsh, Heath, Vom Lehn, and Cleverly [55] (2005)
	Device Landscapes	Stolterman, Jung, Will, and Siegel [124] (2013)
	Web of Technology	Brodersen and Kristensen [25] (2004); Brodersen, Bødker, and Klokmose [24] (2007)
	Ecology of Goods	Pantzar [107] (1997)
	Web of Computing	Kling and Scacchi [73] (1982)
	Digital Assemblages	Sawyer, Crowston, and Wigand [119] (2014)
	Product Ecology	Forlizzi [44] (2007)
	Product Environment	Margolin [91] (1988)
	Personal Information Ecosystems	Tungare, Pyla, Pérez-Quiñones, and Harrison [132] (2006)
	Mobile Kits	Mainwaring, Anderson, and Chang [90] (2005); Oulasvirta and Sumari [105] (2007)
	Multi-Display Environment	Biehl, Baker, Bailey, Tan, Inkpen, and Czerwinski [13] (2008)
	Ecology of Devices	Rick [114] (2009)
	Ecology of Tools	Balakrishnan, Matthews, and Moran [8] (2010)
	Technology Ecology	Chu and Quek [31] (2013)
	Technology Assemblages	Jarrahi [62] (2014)
	Constellation of Technologies	Rossitto, Bogdan, and Severinson-Eklundh [116] (2014)
	Flexible Ecologies	Luff, Yamashita, Kuzuoka, and Heath [89] (2015)
	Personal Ecology	Dittmar and Dardar [39] (2015)
	Web of Artifacts	Bossen [22] (2002); Bardram and Bossen [9] (2005)
	Device Ecology*	Coughlan, Collins, Adams, Rogers, Haya, and Martín [34] (2012)
	Device Ensembles*	Sambasivan, Ventä, Mäntyjärvi, Isomursu, and Häkkilä [118] (2009)

Table 3. Primary publications use the Artifact Ecology terminology. Secondary concepts indicate work that is categorized as similar to Artifact Ecologies. Concepts marked* indicate a terminological overlap with concepts in Device Ecologies (see table 4)

the information ecology, it is not surprising that some of these concepts (e.g. *technologies of literacy* [26], *ecology of ubiquitous socio-technical relations* [32], and *ecology of infrastructure* [123]) refer to the field of STS.

This interest in the lived and experienced environment is also seen in cultural ecologies, where Bell [10] speaks to the background of cultural ecology as coming from the 1960s and being interested in the co-evolution of culture and the lived environment. Other relatively minor concepts within this space also include Turner [133], while discussing information ecologies and other ecology work used to understand people, practices and stuff, takes a similarly big picture while connecting with different philosophical and psychological concepts; and *socio-cultural ecology* by Pachler et al. [106] which argues, in the case of mobile learning, against activity theory for addressing a socio-cultural ecology where the agency of people, their cultural practices and social structures are dominant conceptual aspects.

Examples of use of these types of concepts include libraries [46, 100], an intensive care unit of a hospital [100], a self-service copy shop Nardi and O'Day [100], museums [10], teaching and learning settings [106, 149], and long term research projects [6].

4.2 Artifact Ecologies

While the origin of the term seems to come from Krippendorff [76] as *ecology of artifacts*, as an influential concept for our purposes, the more common term seems to be *artifact ecologies*, which has undergone conceptual development along two strands, one starting from Jung et al. [67]. This has been more widely adopted and built upon for further development of *artifact ecologies*, as discussed here, and for the development of other concepts, e.g. Device Landscapes [124], as well as some of the work on *device ecologies* presented in the next section [57].

The common interest among *artifact ecology* and similar concepts is on foregrounding the relationships of artifacts to practices (both what they are, and how both change), in the context of individual persons or groups of people. As such, it seems less common (compared with *information ecologies*) that people are necessarily included as part of the ecology. While there is an interest in the multiplicity of people, stuff and activities, the foreground tends towards the activity shaped by the artifacts, as opposed to the cultural and big-picture dimensions of *information ecologies*.

The dominant strand of use of the term artifact ecologies as it has arisen from the work of Jung et al. [67] began with an initial focus on the personal ownership and use of different artifacts as part of daily practice. Here Jung et al. [67] define a personal ecology of interactive artifacts as *"a set of all physical artifacts with some level of interactivity enabled by digital technology that a person owns, has access to, and uses"* [67, p. 201] and include a mix of qualitative methods, including visual mapping, which has been built on by Bødker et al. [21]. Theoretical work that has built on this to ground artifact ecologies within activity theory includes the Human–Artifact Model [16], articulating the dialectical way in which the ecology-at-large changes [17].

In contrast to the activity theoretical grounding of the first strand, Vyas and Dix [140] briefly distinguish their unrelated strand of artefact ecologies from activity theory (as well as other theories such as distributed cognition and struturation theory), based on what they suggest is a common *"lack of support for embodiment and materiality"* [140, p.5]. Enquist et al. [41] defined an ecology based on its functional role: *"functional set of artifacts, people and the surrounding environment, in combination with the rich interaction between people and devices we identify as an 'interaction ecology'"*[41, p.9]. Examples of where artifact ecology concepts have been applied include understanding personal ownership and use [63, 67, 90, 105], and groups of people (e.g. local communities [20] or research collaborators [103]), the intersection between [21], or in specific activity domains, such as personal calendar management [38, 39] or collaborative writing [80]. The concept has been used with a basis in activity theory [16] and more recently with distributed cognition [136].

4.3 Device Ecologies

To contrast with the focus on culture, place, activities and people of the previous two influential concepts, device ecologies instead put the devices, how they are connected and how we can understand the workflow across devices, at the forefront. It is understandably the closest of the influential concepts to the field of ubiquitious computing, and is also related to cross-device interaction research (see [27]). We see *device ecologies* defined by Loke [85, pp. 559–560] as: "consisting of devices (in the environment and on users) interacting synergistically with one another, with users, and with Internet resources, undergirded by appropriate software and communication infrastructures that range from Internet-scale to very short range wireless networks". This work has been referenced by other authors including Bellucci et al. [11], Coughlan et al. [34] within device ecologies, and, for example, Chu and Quek [31], Vasiliou et al. [136] regarding other concepts.

Ryan et al. [117] introduce device ecology as being built on the framework of previous artifact ecology work [67]. Their work is mainly referenced by members of the same research group in relation to other concepts, as well as other artifact ecology work. Ultimately this strand seems fairly minor but speaks to overlaps between what device and artifact ecologies seek to achieve. Finally, there is work by Houben et al. [57], which also builds on Jung et al. [67] while also connecting with activity-theoretical artifact ecology work [16, 17]. Houben and colleagues maintain an interest in

Device Ecologies		
Primary	Loke [85] (2003); Loke and Ling [86] (2004); Loke, Ling, Butler, and Gillick [87] (2005); Indrawan, Ling, and Loke [60] (2007); Ryan, Stolterman, Jung, Siegel, Thompson, and Hazlewood [117] (2009); Houben, Tell, and Bardram [57] (2014); Bellucci, Díaz, Aedo, and Malizia [11] (2013); Mercier [98] (2014); Jokela, Ojala, and Olsson [66] (2015); Houben, Marquardt, Vermeulen, Klokmose, Schöning, Reiterer, and Holz [56] (2017); Martinez-Maldonado, Goodyear, Kay, Thompson, and Carvalho [96] (2016); Martinez-Maldonado, Goodyear, Carvalho, Thompson, Hernandez-Leo, Dimitriadis, Prieto, and Wardak [95] (2017);	
Secondary	Ambient Ecologies	Goumopoulos and Kameas [49] (2009)
	Device Ensembles	Schilit and Sengupta [120] (2004)
	Ecologies of Interacting Artifacts	Zaharakis and Kameas [147] (2008)
	Digital Ecologies	Liu, Dyachuk, and Deters [83] (2008a); Wang and Deters [143] (2010); Newon [102] (2011); Yee, Quek, Endert, Chung, and Sawyer [146] (2012); Raptis, Kjeldskov, Skov, and Paay [110] (2014); Bagnara and Pozzi [4] (2016)
	Display Ecosystems/Ecologies	Terrenghi, Quigley, and Dix [129] (2009); Anzengruber, Castelli, Rosi, Ferscha, and Zambonelli [3] (2013); Huang, Mynatt, and Trimble [59] (2006)
	Personal Smart Spaces	Papadopoulou, Gallacher, Taylor, and Williams [108] (2012)
	Ubiquitous Computing Ecologies	Marquardt [93] (2011); Ledo, Greenberg, Marquardt, and Boring [81] (2015)
	Service Ecologies	Dyachuck and Deters [40] (2007)
	Multiple-Device Ecology	Dearman and Pierce [37] (2008); Houben, Vermeulen, Klokmose, Marquardt, Schöning, and Reiterer [58] (2015); Cecchinato, Cox, and Bird [29] (2017); Blumenstein, Kaltenbrunner, Seidl, Breban, Thür, and Aigner [15] (2017)
	Palpable Assemblies	Ingstrup and Hansen [61] (2005)
	Interaction Ecologies	Enquist, Tollmar, and Corry [41] (2007)

Table 4. Primary publications and secondary concepts categorized as similar to Device Ecologies.

the way in which activities and devices are managed, the different roles that devices take, the way in which technical configuration and connection is between devices is established (both technically and from a usability perspective).

As the interactions between devices is important in understanding and developing device ecologies, it is no surprise that this often involves lab and user studies [57], technical work following business processes [85], and current UbiComp topics e.g. smart homes [49] and proxemics [81].

4.4 Communicative Ecologies

Communicative ecologies include work that focuses primarily on communication technologies in relation to practices and communities. Whereas other positions discuss tools used for communication as part of a information ecology or artifact ecology, the following publications take an onset in communication needs or the challenges related to mediating between distributed ecologies, mixing with physical places, and interactions with the digital as mixed realities. In naming the concept, we chose communicative ecology over media or mediating ecologies because of a common reference to Altheid's work on communicative ecologies [2].

The key notion in communicative ecology is that the same technology can be used to for different purposes and evoke different meanings in different contexts [45, p.757]. In order to examine these local appropriations and meanings it is necessary look not only at the communication media, but also include the social interactions and content. Thus, a communicative ecology is defined along three dimensions: a technological, social, and discursive [2, 131].

The concept (including minor positions) has been applied in several ways in the categorized literature: (1) As a technology-centric analyses where studies examine the list of different communication technologies within a particular domain, e.g. the appropriation of communication technologies and social media services within the workplace [64, 134], among students [97], in activism [109] and in a scavenger hunt [48]; (2) with a focus on how (novel) communication

	Communicative Ecologies	
Primary	Altheide [2] (1994); Tacchi, Slater, and Hearn [127] (2003); Tacchi [126] (2006); Foth and Hearn [45] (2007); Turner, Qvarfordt, Biehl, Golovchinsky, and Back [134] (2010); Memarovic, Langheinrich, Rubegni, David, and Elhart [97] (2012); Gonzales, Fiesler, and Bruckman [48] (2015); Treré and Mattoni [131] (2016)	
Secondary	Fractured Ecology	Luff, Heath, Kuzuoka, Hindmarsh, Yamazaki, and Oyama [88] (2003)
	Hybrid Ecologies	Crabtree and Rodden [35] (2008)
	Sociotechnical Ecology	Jarrahi and Sawyer [64] (2012)
	Dual Ecologies	Kuzuoka, Kosaka, Yamazaki, Suga, Yamazaki, Luff, and Heath [79] (2004)
	Mixed Reality Ecologies	Kirk, Crabtree, and Rodden [70] (2005)
	(New) Media Ecology	Pearson and Trevisan [109] (2015); Treré and Mattoni [131] (2016)
	Social Media Ecology	Zhao, Lampe, and Ellison [148] (2016)

Table 5. Communicative ecologies: Primary publications and secondary concepts categorized as similar to communicative ecologies.

technologies can *mediate* between multiple locations and distributed actors in collaborative activities, e.g. how collaboration and interactions are mediated by a mixed reality game [35], how novel systems can mediate gestures and bodily interactions between different locales using controllable robots controllable robots [79, 88] or video overlays [70]; and (3) within specific communities and analyzing the relationship between social interactions and discourse, and then the mediating technologies, e.g. how complex networks of social relations emerge through online interactions on community boards and social media [45], or a social movement and how they are shaped by all three dimensions of communicative ecologies [131].

5 THREE LEVELS: MACRO, MESO, MICRO

The influential concepts above span three conceptual or analytical levels when considering *what* an ecology is. These levels are useful for understanding the existing work, the kind of foci they takes and the object of interest. We propose that they can also aid future work on ecological perspectives by offering a way to position current and future work, an entry point into the multiple ecological perspectives.

5.1 Macro: Organisations and activity system(s)

Several, in particular early works deal with ecologies of tools, practices, people, information, etc. on a macro level. The work frequently seeks to direct attention to the socio-technical process that affects or implicates knowledge work and the role of IT within organisations. Several works from the 1980s and 1990s articulate information ecologies as a primary challenge in organisational knowledge management, for instance. Kling and Scacchi [73] shift perspective from a discrete entity conceptualisation of technology to a networked understanding (web of technologies). Here, a computer system is conceptualised as *"an ensemble of equipment, applications, and techniques with identifiable information processing capabilities"* [73, p.7]. In their analysis, the authors focus on activities and what people actually do with technology, how they adapt and appropriate technologies to fit local tasks and requirements, and the (invisible) work that is crucial in making IT work ([73, p.18]). The macro level analysis is often connected to and cite Nardi and O'Day's [100] articulation of information ecologies and to some degree Bell's work on museums as cultural ecologies [10], while other work regards the domains of, e.g., organisation [73], knowledge management [28], culture [125] and place [82, 100]. Later work focus on media ecologies within a larger community context and social groups, e.g. activism [109, 131].

These works share commonalities when they approach the vocabulary and analysis from a macro perspective, taking onset in organisations and places. They use cases and examples as arguments for adopting a high-level conceptualisation of the role of technologies in particular practices and domains. Also they tend to position people inside the 'ecology', as part of an activity system or as a crucial component in making the information ecology work. For instance, Nardi and O'Day envision an information ecology as *"[. . .] a richly patterned collaborative system of users, human agents and software agents."* [101, p.86].

5.2 Meso: People and practices

A large section of the literature explores and discusses artifact ecologies from the perspective of practices and collaboration. This work varies from examining how larger (urban) communities adopt and negotiate technologies [55], how residents [45] or community groups [21] interact in/through communicative ecologies, web of artifacts in and across work settings, e.g. disperse physical plants, [12], research [123] or hospital/medical work [9], and closing in on a micro level analysis, how students negotiate the collaborative tools around academic work [80, 116], or how remote collaborators coordinate [88].

The meso level work spreads over several or the dominant perspectives, in particular artifact and communicative ecologies. At this level practices and collaborations are studied in work as well as in other forms of communities, often in some form of civic setting. Technologies are considered the means used to carry out these practices and often they are looked at as dynamic and changing, and hence influencing the development of the involved practices. Many of these practice-based approaches are not particularly concerned with building up a theoretical or conceptual foundation, often due to their ethnomethodological inklings. Some of them, however have been important for the development of the perspectives of infrastructuring, and others have built on their foundation in Activity Theoretical HCI to build up a conceptual basis, addressing the level of people, practices and technologies together.

5.3 Micro: Individuals, artifacts and tasks

In addition to these two levels, some work in the survey has a conceptual focus on atomic aspects of an ecology, in particular we have found a number of papers with a focus on individual people or individual artifacts, or for that matter particular activities or tasks. Each analytical 'anchoring point' develops from a few key papers: The focus on the individual develops from Mainwaring et al. [90] and Jung et al. [67]; the focus on the artifact develops from works within design theory, primarily Krippendorff [76]; and less researched, task-centered focus, e.g. Bouvin et al.'s [23] detailed comparison of technologies for map use.

It is relevant to highlight here the work of Bødker and Klokmose [16] and in particular [17] on the Human-Artifact Model (as part of developing artifact ecologies grounded in Activity Theory), which provides a means through which to look at both individual people and individual artifacts as foci within an ecology. Bødker and Klokmose [17] and [18] focus on the role of smart phones in shifting the personal artifact ecology of their users. In this manner this particular analysis is an example of an analysis that concerns both *a particular person* and *a particular device/artifact*. The personal artifact, as part of an artifact ecology is the starting point of [67] as well as of later examples of calendars by Dittmar and Dardar [38, 39]. Particular artifacts are in focus in much recent work on cross-device interaction, hence device ecologies, e.g. [58, 81] where the conceptual work is aiming to understand how artifacts move or are distributed across devices, depending often on the needs arising from specific forms of collaboration or movement of the activity. Even at this level, the conceptual build-up between cases and papers is quite week, again with the exception of Activity Theory based papers.

5.4 Levels in summary

We have seen some connection between levels of analysis and dominating perspective, yet as with the perspectives, these levels are not very well conceptualized in the work for the most part. Publications tend to be implicit about the analytical scope of the work, suggesting that the presented concepts operate on multiple levels. Key challenges in moving forward is research that explicitly targets each level, further defining the upper and lower bounds, and the appropriate empirical and analytical tools, and design interventions; and subsequently connects the three levels with sufficient theoretical and socio-technical quality. As it is now, empirical and conceptual work is 'over represented' at the macro and meso level, while constructive work dominate the macro level (see e.g. [27]).

6 CROSS-CUTTING THEMES AND PERSPECTIVES

Here we reflect on themes that cut across the major and minor concepts, primarily developed from works has a conceptual element and analyse and synthesise concepts (see table 1). This serves both as a guide to the existing work on ecological concepts and suggests future directions for work on ecological concept HCI research.

6.1 Collections of technologies

Ecological concept research within HCI takes a number of different positions on *what* is in an ecology concerning tools or technologies, both in the present sense of what is here now, as well as the historical development and hypothetical future (design more generally). Several challenges emerge when works make decisions on what to include in an ecology concept: First, regardless if the ecology is defined by people *and* technologies, as belonging to organisations, communities or individuals, or by being present in a given context, the analysis typically lets the object of study and/or design be the deciding factor. This frequently turns in to naively 'doing inventory' or a narrow technological focus. Second, a majority of the work focuses on *computational* technologies, often giving them a prominent position over non-computational artifacts. Very few publications reflect on this dichotomy or the implications for what is studied and designed. As Bødker and Klokmose point out, making unwarranted distinctions between the 'physical' and 'digital' is not fruitful [p.3 18]. While perhaps beneficial in setting the stage and focus for a study or prototype, it limits the conceptualisations and nuanced understanding of what an ecology concept describes.

A few positions discuss nuances on what is in the ecology based on functional and situational needs: Oulasvirta and Sumari [105] make a few useful distinctions between the *active subset*, the artifacts (devices and non-computational support) in momentary use, and the *passive subset*, those physically available, but not currently used. Similarly, Rossitto et al. [116] and Larsen-Ledet et al. [80] discuss the *aligned part of the ecology* as the tools agreed upon among collaborators and the *potential part of the ecology* as those familiar and available to the sum of collaborators, if needed. These distinctions describe the detailed dynamics of ecologies and provide useful analytical concepts to be further developed. By contrast *communicative ecologies* focus entirely on technology that serves the purpose of communication, while also not distinguishing between physical and digital [2].

6.2 Boundaries and contexts

Related to the conception of tools and technology above there is, in the works, a more general sense of where an ecology is anchored and where it draws its bounds. For instance, Bødker et al. [20] use the community studied as the bounds of the ecology, while also including (but distinguishing) the external events and factors (e.g. device rental costs, or regulatory requirements) that lead to different technology design and use. Mainwaring et al. [90] and Jung et al. [67] by contrast focus on individuals as the bounds of the ecology. Other examples include particular settings, e.g. meeting spaces [140], libraries [101], apartment blocks [45] and classrooms [136]. Finally, Krippendorff [76] and Forlizzi [44] put the artifact in the centre and examine these through its various contexts.

What is within the ecology is negotiated, roughly speaking, between what is there, what users are familiar with, and what is needed [25, 105, 116]. These negotiations also happen at the boundaries between different ecologies. Rossitto et al. [116] describe how students negotiate tools both in advance and when needs arise. Bødker et al. [20] describe how a community's ecology originate in the founding members personal ecologies. Throughout the lifecycle of the community, these are further negotiated as responses to external and internal events [19]. Larsen-Ledet et al. [80] draw on the above work and propose a model for examining the influences from multiple (personal) ecologies, as *transitions* across multiple personal artifact ecologies, and imply that these may be mechanisms for more permanent integration of new tools into an ecology.

6.3 State and evolution

A majority of the publications recognise that ecologies are not static. They change and evolve [16, 19, 100, 132]. This is closely linked with adopting the concept or metaphor from biology and in Nardi and O'Day [100] who note that *"[i]nformation ecologies evolve as new ideas, tools, activities, and forms of expertise arise in them"* [100]. The notion of development within ecologies is further linked with how new tools are adopted and appropriated [see 128]. The conceptual understanding of change of and in ecologies is significantly underdeveloped, e.g. Oulasvirta and Sumari [105] only examine what is active and passive in use, Enquist et al. [41] see a functioning ecology as a defining trait of an ecology and Sambasivan et al. [118] discuss various scenarios of situated non-use, where certain artifacts are abandoned over time. Tungare et al. [132] discuss evolution and equilibrium as traits of a healthy ecology and how change happens gradually. Bødker and Klokmose [16] develop a state-based model and understanding of the dynamics of artifact ecologies (from the perspective of an individual person). When an ecology no longer fulfills the needs and expectations of the individual, it enters the unsatisfactory state. When a new tool is added it enters an excited state, and when the ecology fulfill the expectations of the user, it is in a stable state. Bødker et al. [19] discuss change over time within a community and their artifact ecology as a mix of happenstance, strategic effort and tactical responses [36] to internal and external circumstances. They show, through a series of models, the different changes within the community artifact ecology and the links to specific internal and external events.

6.4 Open challenges and future research

The themes above invite substantial further research. One of the primary challenges is that the concepts that show potential are centered around few publications concentrated on the meso and micro levels, predominantly within work on artifact ecologies (see table 1) and the theoretical foundation informing this work. Instead of identifying concrete research gaps in the existing work, we propose that future research follows a series of expansive steps grounded in the work reviewed here. Foremost, engage with the existing work withing the influential concept and level relevant to the research at hand. The concepts and themes highlighted above are still underdeveloped and rarely applied, analyzed and synthesised into coherent frameworks. For instance, the discussions of active and passive [105], and aligned and potential elements [116] of the ecology need additional empirical and conceptual work before they can inform design and constructive research; second, horizontal moves along the axis of research types, from empirical to constructive and back, could improve and help extend the existing concepts; and third, vertical moves across the three levels, macro, meso and micro, could help integrate the different concepts into more coherent perspectives.

7 DISCUSSION AND CONCLUSION

The rationale for conducting this survey was *to read a lot of papers so others do not have to* and try to connect ideas and concepts across a body of work that span 129 papers and 54 concepts. The driving thesis has been that while a lot of this work stands isolated and underdeveloped, there must be commonalities and conceptual developments. Our analysis and synthesis indicate that these commonalities can be condensed into four influential positions. We also draw out analytical levels and themes that can inspire application and further developments within the research community. These are the primary contributions of the paper. For the remainder of the paper we highlight and discuss two interconnected issues emerging from the review: The disconnected nature of the corpus and our concern regarding the current state of theorising in HCI and beyond.

7.1 Disconnected Work

When initiating this review we were familiar with multiple diverse works on the topic. Hence, it is no surprise that substantial parts of the corpus stand as somewhat disconnected in terminology, references, research types and genres. However, we have also uncovered underlying cases of 'conceptual carelessness' significantly contributing to the disconnectedness of the concepts.

In the first example different disconnected stands of work apply the same terminology without strong connections between them. *Digital ecology* is one that has two strands of development, one that leads from [84, 110, 143], another from [95], in addition to multiple works that do not recognise the conceptual origin: [35] use the term as an umbrella term under which their work on Hybrid Ecologies sits, Bagnara and Pozzi [4], Newon [102] use the words descriptively (in [50] terms), and Yee et al. [146] use the term as part of their analysis. Another example is *artifact ecologies*, originating with Krippendorff [76] as *ecology of artifacts*, and referenced by Jung et al. [67], but disconnected from Vyas and Dix [140]. Jung et al. [67] drew on multiple perspectives including the information ecologies and were used by Bødker and colleagues [17, 20, 21]. Separate to this, Oleksik et al. [103] introduced the term, as a specific type of *information ecology*.

The second case is where the same group of authors use multiple concepts without distinguishing the difference. Examples of this include: *fractured ecologies* [88] and the later *dual ecologies* [79]; or *web of technologies* [24, 25] and *artifact ecologies* [16]. Stolterman and colleagues introduce *Personal Ecologies of Interactive Artifacts* in their 2008 paper based on empirical work where they overlap [67]. A year later they discuss a digitization of their empirical mapping method under the conceptual heading of *Device Ecology Mapper* and *Ecosystems of Interactive Artifacts* (and *Personal Artifact Ecosystems*) without discussing the terminology beyond citing [117, Title & Fig 1.]. In 2013 they further discuss *Device Landscapes* [124], again without discussing or bringing between the concepts *they* have proposed earlier. This includes explaining different concepts using the same figure ([124, Fig 1.] and [124, Fig 1.])[2].

The last is the more general case of authors introducing a new term or concept, without discussing why previous terms (often mentioned or cited as related work) were insufficient. Some examples of this include *constellation of technologies* that could probably have just continued to use *artifact ecologies* and the work would be no less valuable [116]. Different theoretical foundations are used with concept development leading to potential ambiguity that ensues: Bødker and Klokmose [16] establish an Activity Theoretical foundation for *artifact ecologies*, and later Vasiliou et al. [136] apply Distributed Cognition to the same theory without reflection on the prior theoretical work.

Similar terms ascribed with different meanings, and vice versa, creates more opportunity for fallacies of equivocation and ambiguity within research work. This is distinct from the ways in which concepts develop and evolve over time,

[2] Similar can be observed in work by Dittmar and Dardar, cf. [38, Fig. 3] and [39, Fig. 3]

where a concept build up more baggage and get pushed in different directions. If there is a rift or division, a split of a concept that may be useful, but having multiple 'minting' of the same words serves more to muddle the research communities understanding. We wish to draw the research communities attention to this, as there is a danger in creating ambiguity in how concepts are defined, introduced, and used. The remedy is first and foremost in the craft of research and academic rigor.

7.2 Concerns on the current state of theorising

We are all embedded in our research practices, and we are often working across disciplinary boundaries, drawing concepts, frameworks and theory from a multitude of sources. As such, we understand that engaging in work that misses literature happens, even if supported by a peer review process. While the development, extension and creation of theory is important to build on the foundations of HCI, we recognise there is a certain currency and legitimacy to be earned as researchers by coining something new and exciting, to differentiate ourselves and create a legacy. It seems unclear, and perhaps characteristic to the relative age of the HCI field with regard to theory, how and when contributions to the discourse about 'ecology' concepts warrant a new or expanded name.

While our critique here serves as an attempt to discipline the use of these theoretical concepts within HCI, we do not wish to act as gatekeeper, but rather push the conversation towards a clearer and shared understanding of what these terms refer to, and where they can be useful. If we assume that the body of knowledge reviewed represents a developing body of knowledge that can be synthesised into integrated conceptual and theoretical components over time, then current practices and state of theorising in HCI raise a few concerns.

Based on the ways in which research is valued in HCI, with a focus on a need to create something novel and exciting, we speculate that a new term serves to emphasise the proposed concept as something different. For researchers not wanting to misinterpret an existing theory or concept, creating a new one is a way to 'hedge ones bets' and avoid diluting or introducing confusion around the existing ones. Based on the number of concepts we have seen, we are not convinced this is effective. A strategy of creating a new concept also serves as a way of trying to distance it from theoretical baggage that surrounds the other concepts. When terms are used in different contexts, or different sub-fields one may also try to avoid confusion by a new concept. For some authors, this may limit the breadth and scope of how they relate to existing work. Given the quantity of research papers and the pace with which the production of new papers moves within HCI, it is understandable that a lot of parallel work is done.

While we have sought to show a rich diversity in work that engages with these terms, and help researchers know the different influential concepts, we have also shown a number of examples of confusion and ambiguity. We conclude with a call for future work to strengthen the capability and vocabulary of the concepts in general. The four influential positions would be a good place to start, if not with some of the other existing concepts. With a plethora of 54 concepts, an argument for a new way to describe and analyse the multiplicity of people, stuff, places, etc. would need to not only engage meaningfully with existing work, but to against existing concepts, lest it muddies the conceptual waters further.

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