"Beautiful Seams":

Strategic Revelations and Concealments

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ABSTRACT

This paper tracks a debate that occurred, first, within the field of Ubiquitous Computing but quickly spread to CHI and beyond, in which design scholars argued that seamlessness had long been an implicit and privileged design virtue, often at the expense of seamfulness. Seamless design emphasizes clarity, simplicity, ease of use, and consistency to facilitate technological interaction. Seamful design emphasizes configurability, user appropriation, and revelation of complexity, ambiguity or inconsistency. Here we review these literatures together and argue that, rather than rival approaches, seamful and seamless design are complements, each emphasizing different aspects of downstream user agency. Ultimately, we situate this debate within the larger, perennial discussion about the strategic revelation and concealment of human and technological operations and therein the role of design.

CCS CONCEPTS

• Human-centered computing → **HCI theory, concepts and models.**

KEYWORDS

Seamful and seamless design; infrastructure; ubiquitous computing; temporality.

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1 INTRODUCTION

If something has been taken over for me, is there a presentation of what has been taken over that I can bring to the fore whenever I like, including retroactively? – Mark Weiser [50]

A longstanding issue for technology design, particularly information technology, is how much of its internal operations to reveal or conceal from its users. Often, systems are described as usable or transparent, valuing their tidy or simple arrangement, but at other times we value their configurability and seek deeper understandings of the detail and complexity of the system. Some studies cast the issue negatively, such as the 'black boxing' of machine learning or algorithms [21]. Others laud what seems the very same thing, such as 'infrastructure', which presents a generally positive valence for getting potable water from faucets without having to encounter the process of purification, or conducting high-performance computing without the hassle of setting up a complex architecture [37, 38]. The "cloud" is a particularly vivid divergent case today, as some [2] point to a novel arrangement enabling easy storage, representation, and computing, while others call for remembering the forgotten materiality of computing [18] and its increasingly distanced environmental consequences [36]. Taken as a whole, neither the revelation or concealment of technological action can be approached as a simple virtue or vice; rather, it is a central topic we wrestle with in the abstract but must ultimately resolve in design practice.

The matter is particularly pressing today, as, for example, the revelation and concealment of the operations of technology are relevant to everyday lives (e.g., what is or is not captured in activity on social media [17]), national and global politics (e.g. what nation is influencing this or that electorate), and to science and engineering (e.g. what data transformations have occurred to make evidentiary claims [37]). In 1996, Susan Leigh Star [45] observed the dual meaning of transparency; in technical circles, transparency

acted as roughly the equivalent to ease of use or usability, while in political circles it took an opposite meaning, roughly referring to open and accountable processes. Thus, the matters we address in this paper are both timely, and perhaps, timeless.

Here we will address the matter through a review of what has become a particularly fruitful approach: seamful and seamless design. Roughly, seamless design emphasizes clarity, simplicity, ease of use, and consistency to facilitate technological interaction. In contrast, seamful design emphasizes configurability, user appropriation, and revelation of complexity, ambiguity, or inconsistency. However, these two design approaches have not had an equal standing: until recently, seamlessness has tended to be valued over seamfulness. Seamlessness has a long history preceding its use in information technology, but it is first within Ubiquitous Computing that seamless gained its theoretical complement: seamful. Mark Weiser is perhaps most recognized in his call for seamlessness in Ubiquitous Computing writing that, "a good tool is an invisible tool. By invisible, I mean that the tool does not intrude on your consciousness; you focus on the task, not the tool" [51]. However, only shortly after Weiser prefigured the critique of seamlessness when he advocated for "seamful systems" or those with "beautiful seams" [49, 53], calling for well-designed configurability and strategic revelation of complexity, error, or backgrounded tasks.

For the first half of this paper we will focus on the debate about seamfulness and seamlessness as it was articulated within, firstly, the field of UbiComp, but then quickly adopted within CHI and CSCW. Here, researchers sought to identify what they asserted was previously an implicit design virtue – seamlessness – and sought to articulate the alternate position of seamfulness by questioning "the assumption that seamless integration of computer system components is necessarily a design requirement" [15]. While we agree with the assertion that seamlessness has been an implicit design virtue, we have found that seamfulness too has long been a design virtue. Our argument, then, is that the critique of seamlessness by advocates of seamfulness has led to a stronger, clearer articulation of both concepts and their design consequences.

A central recurrent concept in the seamful/less literature has been "agency", particularly the agency of the user, but at times the agency of the designer or system. For example, Chalmers [10] writes that "any design makes manifest designers' implicit and explicit assumptions with regard to how to reduce, formalize, or objectify context and activity i.e. the choice for the system designer is not whether to reduce, objectify, or constrain users' context, but *how*." A parsimonious, tidy, clean, or self-explanatory interface grants agency to users by lowering technical barriers of entry, by facilitating quick access to common operations, or offering familiar interactions rather than a cacophony of interface languages. Seamlessness can be enabling. But a highly configurable technology, adaptable to unforeseen circumstances and novel uses, revealing of its complex internal computations, transformations, limits and boundaries, too is enabling *at times and for some*. In short, contrary to what some authors have asserted, increased or decreased agency is not the bailiwick of either seamful nor seamless design.

Throughout this paper, we illustrate these concepts with the cases of design and analysis that have sought to exemplify them. We draw extensively from examples in the literature, but we do not limit ourselves to cases drawn from professional design. It is often specific user groups that modify, build on top of, or hack existing tools to suit their particular needs by adding additional seams. We draw on such cases in ecological science to show how specialized users, such as scientists, create their own, occasioned seams [26].

In the second half of the paper, we trace this discussion past its initial formulations to those who have adopted these concepts beyond UbiComp, CHI, and CSCW. The lineage we follow begins with design but eventually overflows it, becoming a debate about world views: is the extant or ideal world seamless, or, is it fundamentally seamful, perhaps desirably so? Ultimately, the language of seamful/less engages a deeper issue: the revelations and concealments of human and technological operations and their relationship to agency. Fields such as Infrastructure Studies and Science and Technology Studies (STS) have long wrestled with such topics as well, and recently have found some value in seamful/less literature. These discussions thus offer an opening to longstanding questions of technological revelation, concealment, along with those of user, designer, and system agency.

The discussion section assembles conceptual and design techniques developed to inquire upon and enact seamful and seamless design. We conclude with a synthetic view on the seamful/less debate, casting it as a mutual conceptual articulation.

2 METHODS AND ANALYTIC APPROACH

In our review, we were particularly concerned with the following questions:

- How have seamlessness and seamfulness acted as implicit design virtues?

- How have critiques of seamlessness led to a stronger articulation of the concept, along with opening the possibility of seamfulness as a design virtue?

As the paper proceeds, the second half is concerned with:

- How has the concept of seamfulness been taken up in fields outside of design?
- How do seamfulness and seamlessness speak to broader issues of technological and human revelation and concealment, and of user, designer, and system agency?

Our discussion and conclusion return to design to ask:

- What are the different techniques or 'tricks of the trade' for doing seamless and seamful design?

Our review is based on articles found on two database platforms available online: ProQuest and Google Scholar. We conducted our search during August 2017-August 2018 using the following keywords: "seamless design" "seamless" "seamful" "seamfulness" and "seamful design". In our initial search, we only included the first 150 papers that mentioned "seamful", only peer-reviewed articles, and only those studies published in English. Although seamfulness comes from Ubiquitous Computing, we did not restrict the search to design or ubiquitous computing fields. Additionally, for some highly cited papers, we sampled the first 30 papers from those that cited the paper to understand how researchers and practitioners have used the term. Finally, we reviewed all papers that mentioned seamful in the abstract within ACM's CHI digital library.

Limitations of this review include the inability to probe other discussions on similar themes if they are not using the term 'seamless' or 'seamful'. In this way, the work is specifically focused on the language of seams and how it has evolved amidst shifting technological and societal changes. While issues of temporality, invisibility, and uncertainty are not solely in the domain of seamful/less literature, we see these overlaps as speaking to the broader impacts of this literature review.

Both seamful and seamless design are often concerned with what users can or cannot do, and to a lesser extent what designers or systems can (or should) do. Agency is often addressed directly in the seamful literature, while more tacitly in discussions of seamlessness. For example, Sengers and Gaver [42] argue that seamful designs "explicitly represent the limitations and uncertainties in data, allowing users to make up their own minds about how to interpret it."

In this paper we will not offer a definitive definition or theoretical stance on "agency", instead, as is appropriate for a literature review, we will closely attend to how various formulations of agency have been deployed by the authors we review. The advocates of seamlessness have drawn attention to certain enabling and disabling properties of design, while the advocates of seamfulness have emphasized others. Here we present them together, without offering a resolution as such, but instead seeking to sustain the tension between them. We believe the tension is not resolvable in the abstract; once again, it is a matter of strategic revelation and concealment in situated design decision-making. Thus, we seek to render available for consideration what is at stake in decisions for and against seamless and seamful design, as well as provide techniques for considering the downstream consequences that follow from such design decisions.

Occasionally, in the literatures we review here, authors have approached seamfulness and seamlessness as opposites, even taking stances against one or the other. However, as in their original formulations, here we will approach these concepts together as complements. Taken together these concepts suggest that decisions about revelation or concealment, simplicity or configurability, should be strategic, recognizing that both can be enabling even while each exacts a cost. We hope the term "strategic" evokes a situated designer making consequential decisions that, even when following the best available process, ultimately, faces uncertain downstream trajectories of use.

3 SEAMFUL AND SEAMLESS DESIGN

It is more challenging to find explicit definitions of seamlessness than its counterpart, particularly at the moment we pick up this debate in the early 2000s. Early papers that sought to articulate seamfulness argued that seamlessness was a longstanding, implicit design virtue for computing, interfaces, and systems. From our literature review, they are largely correct. As a taken-for-granted virtue, most uses of the term seamless are not accompanied by a definition, explicit argumentation about the value of seamlessness, nor empirical investigation of its practical instantiation. There is a vast literature on how best to achieve seamlessness in its many forms, but very little on whether seamlessness *should* be a priority. As such, assembling a definition for seamless design from the literature involves inferring from heterogenous uses, inconsistent definitions, and sometimes contradictory justifications. Below we first seek to assemble an understanding of seamlessness from its advocates, but

ultimately, the most cogent definitions come from those espousing seamfulness, as they set themselves to the task of articulating what had thus far proceeded as a tacit design virtue. Following this, we trace uses of seamful design in UbiComp, and then more broadly in CHI and CSCW.

3.1 Seamlessness

Mark Weiser was first to explicitly articulate seamfulness for the Ubiquitous Computing research community. His writings are historically situated in an era in which the move to push personal computers "into the background" [51] promised to take users into more collaborative environments. In *The computer for the 21st century* [51], Weiser introduced a vision for Ubiquitous Computing that highlighted the seamless integration of computers into a world where screens would largely be backgrounded, relinquishing demands on our attention.

This set up Weiser's proposal for calm or ambient technology, which he developed with John Seely Brown. The justification for calm technology is that it engages "both the center and the periphery of our attention" and "moves back and forth between the two." They defined periphery as "what we are attuned to without attending to explicitly." They drew on an example of driving and how attention is not focused on the engine until an unusual noise occurs. Regardless of the name (e.g. "calm", "ambient", "invisible"), the sentiment is the same: that the ideal in an era that increasingly values seamless interaction is that a computer should become so embedded, "so fitting, so natural, that we use it without even thinking about it" [54].

However, as early advocates of seamfulness argued, seamlessness preceded these explicit formulations of its meaning, long serving as a tacit design virtue. Early visions of seamlessness operated in a space that valued technology as invisible or backgrounded to the user. Writing for the CSCW community, Ishii [6] noted that "existing individual workspaces must be integrated so that users can shuttle smoothly between their individual workspaces and the virtual shared workspace." In this vision, seams were problematized as something that needed to be overcome. In later work by Ishii, the seamless solution to reconciling the disjuncture between physical and digital space was to encode physical objects with digital information. In this way, the act of coupling the digital and physical seamlessly extended the digital realm by taking advantage of "natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information" [28].

Following this, initial CHI research that drew on the word "seams" treated them as undesirable, something to be designed out or overcome, again taking seamlessness as an implicit virtue. In this vision of seamlessness users needed not to think or be confronted with any cognitive discontinuity, lest they reject the tools [23]. Furthermore, seamlessness was presented as a novel design challenge, an opportunity to investigate how to overcome these discontinuities between the virtual environment (or user interface) and the actual desktop (or hardware). For example, using Grudin [23] as their point of departure, Mackinlay and Heer [33] argued for "mitigating" seams by creating seam-aware applications. Rather than dealing with issues of disruption between physical and virtual worlds, they were concerned with seams that interrupt a holistic view. One example they used is a graph that does not fit on a single monitor. As such, the image must be stitched together across multiple screens requiring a "seam-aware" system.

Taken as a tacit ideal, we can observe how many popularizations and simplified design heuristics drawn from HCI findings take seamlessness to be an implicit virtue. For instance, almost all of Neilsen's classic heuristics [34] for good user interface design can be read as instantiations of seamlessness, e.g., "Users should not have to wonder whether different words, situations, or actions mean the same thing" or by valuing "design which prevents a problem from occurring in the first place." More broadly, almost all handbooks of HCI design encourage smoothing distinctions between the virtual world and the "real world", problematize errors and uncertainties, and call for ease of use, simplicity, and standardized design.

However, the matter is not so simple. Accompanying such embedded valuing of seamlessness in popular design accounts are themes that begin to approach seamfulness. For example, Neilsen's heuristic continued, "either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action." The latter suggestion could be read as the suggestion to create "a beautiful seam" [48], easily revealing an error or presenting the user with a choice. In other words, it may be the case that seamfulness itself has a long history as a tacit design virtue alongside seamlessness; though it certainly appears that seamlessness was cast as a higher ideal, with seamfulness positioned as a pragmatic, second-choice alternative.

3.2 Seamful Design

Initial authors on seamfulness [4, 14, 15, 32] took seamlessness as their foil. They sought to characterize seamlessness as a long standing but unacknowledged design virtue, and as such, they offered various explicit definitions of seamlessness, along with their own reparative concept, seamfulness. Chalmers as well as MacColl, Galani, and Bell did much of the synthetic work in the early 2000s as they highlighted Weiser's initial introductions to seamfulness in his invited talks to UIST in 1994 [49] and USENIX in 1995 [53]. It is in these publications and talks that Weiser suggested that seamful systems may too be a goal rather than pure seamlessness. The initial literature on seamfulness can thus be read as challenging the implicit hierarchy that placed seamlessness as an ideal solution, seeking to debunk the "the assumption that seamless integration of computer system components is necessarily a design requirement" [13]. Below, we present some of the major themes from our review, which we will cover again in the discussion section.

3.2.1 Visibility and Invisibility

Much of the initial work in seamful design was focused on managing the distribution of infrastructural resources (e.g. network connectivity) across space. While equating seamful with visibility and openness, Chalmers et al. [8] equated seamless with invisible and closed—casting them as opposites. In his early writings on seamfulness, Chalmers [13] wrote that a central feature of the work is making seams "into explicit resources for interaction." The project they used to illustrate the usefulness of seams was a "seamful map" designed to allow users to "take advantage of the spatial variation of [wifi] network coverage" by visualizing the areas of varying levels of signal strength around the researchers' university – see figure 1. In the grids colored green, the signal strength is strong; whereas, in areas in red, the connection is absent. They noted that the presentation and visibility of this information could allow users to exploit, rather than be unaware of, uneven network coverage: users could "change an aspect of their non-digital context – [physical] position – in order to change digital aspects of their context such as database accessibility and social aspects such as being reachable by one's boss" [12]. Thus, this seamful design, Chalmers et al. [13] argued, is enabling by allowing users to act with uneven network coverage, rather than finding it to be solely an opaque hindrance.

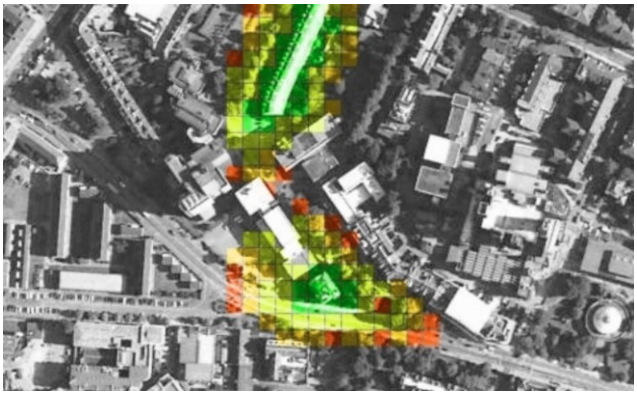

Figure 1: From [13], "seamful" map illustrating the distribution of network connectivity on campus. Image reproduced by permission of the Institution of Engineering and Technology.

Another early example of seamful design in CHI was *Feeding Yoshi* [4], a game played across three different cities. The study centered around uncertainty about network connectivity in the player's environment. Instead of viewing breakdown of connectivity as a problem, they looked at other potential constraints (e.g. financial) around losing connectivity. They noted that system design should not assume that network connectivity is "uniformly and unproblematically available" as users "may have to handle breakdowns and exceptions to this assumption." Bell et al. [4] went on to characterize strategies for dealing with breakdown and explored the "impact of variation or uncertainty with regard to location and network connectivity." Their strategies included removing variation, hiding variation in the system design, managing user activity, revealing variation, or exploiting variation or uncertainty as a design resource. Exploiting and revealing is a particularly seamful approach in that it takes disjuncture to be a resource. As we will see later in our review, such concerns with invisible infrastructure and its potentially deleterious effects dovetail with the core concerns for the field of infrastructure studies.

Chalmers and Galani [14] also refer to "breakdown" or "when the affordances of even the most familiar tool may significantly differ from those of everyday ready-to-hand use". In their paper, they alluded to findings from infrastructure studies, design theorists, and political philosophy when asking how a tool can become invisible [48]. Infrastructural provisions such as network connectivity or electricity are examples of resources that are often metaphorically and physically out of sight. In

an infrastructural sense, breakdown is a method for elucidating what is happening behind the scenes.

3.2.2 Uncertainty and Appropriation

Designing for appropriation is a common theme in the seamful literature. MacColl et al. [32] emphasized two examples of seams in Ubiquitous Computing: uncertainty and appropriation. Chalmers et al. [13] cited Benford as offering four presentation policies for using and presenting seams (specifically with respect to breakdowns in connection to WiFi): pessimistic: showing only information that is known to be correct; optimistic: showing all information as if it was correct; cautious: explicitly presenting uncertainty; opportunistic: exploiting uncertainty [20]. Gaver et al.'s [20] use of opportunistic presentations has become the standard view of seamfulness: that inaccuracies, uncertainties, and boundaries in a system can be exploited as a resource. In other words, that seams or gaps can be seen "as a feature, not a bug." This form of presentation has been popular in user experience design circles as a way of understanding how users behave and what types of design encourage emergent activity. Arguing that ambiguity (or uncertainty) can be a resource for design, Gaver et al. [20] showed that while ambiguity may appear to be antithetical to usability, ambiguity and uncertainty are in fact part of achieving usability.

Around the time that designing around uncertainty was cast as a novel approach, designing applications for game interfaces was a growing interest for researchers as it offered opportunities to merge virtual and physical worlds in ways that more traditional work around bridging the gap between the interface and the physical desktop hardware could not satisfy. Many of these interfaces were within location-based gaming applications that explored how seams between services like network distribution ([4, 5, 8, 14], dynamic cell-coverage [8], GPS resolution [25], and sensor accuracy [13] could be seen as features, not limitations. These were not just seams between virtual and real, but opportunities to explore user behavior [30]. Most of the projects of this kind were based on the challenge of bridging the gap between simulation and the "real-world".

3.2.3 Time and Interaction Histories

Closely related to prior discussion of visibility is the role of the past in understanding or predicting present actions. While Chalmers and Galani [3] highlighted the importance of heterogeneity—spatial, temporal, and technological—it has largely been spatial and technological heterogeneity that is emphasized in applications of seamful design. Much of the work in the early 2000s involved designing location-based applications and games for revealing the seams of network connectivity or providing users an opportunity to appropriate the seams they know exist [4, 10, 13, 14]. A major gap in much of the literature to date are examples of seamful design as it relates to temporality.

Chalmers [9] explored the role of interaction history in shaping present activity highlighting the tensions between revealing and concealing: "presumably we cannot reveal every detail of the entire system all the time, and so we will have to be selective and, to some extent, reductive with regard to the features and processes we open up." To resolve the issues of how to couple and connect systems, he proposed "tracking and logging user activity and making it a resource for users and developers." In this work, he and others in his lab built a tool to "combine logs from PDAs and the server in the seamful game, and overlaying the street map with data on game events and system log data so as to visualize or 'replay' the game." While there are many examples of how a history of interactions can be useful for design, they are largely designed for spatial context. Rather than positioning the user in time, the user is always positioned spatially.

Although still focused on issues of merging physical and digital environments, Crabtree and Rodden [16] pushed forward the work on seams by looking not just at breakdown, but traceability of users, highlighting the ways that seams can serve as mechanisms of interaction. In a study on network use and indoor localization, Savic [39] followed the logs for "usage of data, cell towers, SMSs, and location estimation based on WiFi fingerprints" and used triangulation to localize mobile devices. Again, the focus remained on aggregating and visualizing spatially-relevant observations.

Drawing on the slow technology movement [24], Siân Lindley [31] noted how "unlike concepts such as 'space' and 'place', which have been the subject of careful enquiry and definition, time is considered sporadically and in rather heterogeneous ways." Similarly, in her research in the Change Islands, Sengers [41] highlighted some of these facets finding that in an increasingly automated and technified world, time has become a commodity rather than a contextually important facet for design. As UbiComp considered space as an opportunity to deploy more and more sensors, connecting the physical space with the virtual, time has been delegated in less conspicuous ways. The increase in GPS accuracy may be closely attended to with respect to where it breaks down;

however, less consideration has focused on the disappearance, concealing, or standardization of time.

3.3 Cognitivism and interactionism

The discussion of seamless and seamful design has played out larger debates about cognitivism and interactionism, respectively. In his earlier essays, Weiser [51] characterized invisibility as "a fundamental consequence not of technology, but of human psychology," and drew on formulations from cognitive science and phenomenology, such as Polanyi's "tacit dimension", Gadamer's "horizon", Heidegger's "ready to hand" vs "present at hand" distinctions, and Herb Simon's "compiling". Thus, in its earliest formulations, seamlessness was cast as a virtue through a conceptual coupling with lowered cognitive load, and thus freedom: "only when things disappear in this way are we freed to use them without thinking and so to focus beyond them on new goals" [51]. Such formulations are "cognitivist" in that they took as their exemplar users with discrete mental capacities focused on a well-bounded task, seeking to minimize intrusions, breakdowns, or distractions. The user was cast as having limited attention; shifting focus came at a cognitive cost; intrusions were distractions.

Later, perhaps, Weiser reconsidered these ideas and offered a more expansive non-cognitive definition: "Invisibility is a property of people, technology, and the situation in which we find ourselves" [55] thus, presaging criticisms by advocates of seamfulness that rooted technological invisibility not in (human) nature but organizational and design decision-making.

We use the term "interactionist" in the sense imparted by sociological perspectives such as symbolic interactionism or ethnomethodology, emphasizing collective situated action [6, 46]. The exemplar in interactionist formulations is not of a cogitating user in front of a computer, but rather multiple humans situated in one or more organizational settings, engaging each other, artifacts, and a series of complex and competing tasks that unfold over time. In such formulations, users are inherently encountering distinct circumstances rather than the "well-bounded problems" emphasized by cognitivist researchers, and are continuously and simultaneously engaged in creative problem-solving and organizational accountability, doing so by drawing on resources at hand. In some sense, cognitivism and interactionism represent distinct world-views; in the next section we outline how seamful designers drew on interactionist formulations. Whether seamlessness is necessarily cognitivist, and seamfulness necessarily interactionist remains to be seen, and has not yet received empirical, design, or theoretical exposition.

3.4 From Seamful Design to a Seamful World?

Ultimately, seamlessness and seamfulness speak to longstanding discussions about the revelation and concealment of human and technological operations. As such, this section returns to discussions in UbiComp but then circles outwards to STS and infrastructure studies, concluding by connecting seamful and seamless design to longer historical arcs of design and social theory.

Bell and Dourish [3] cast a wider critique of Ubiquitous Computing, noting that UbiComp not only took seamlessness to be a design virtue, but often assumed it to be a universal ideal, and even at times a description of the extant world: "the seamlessly interconnected world of [UbiComps'] future scenarios is at best a misleading vision and at worst a dangerous one. Homogeneity and an erasure of differentiation is a common feature of [UbiComps' envisioned] future environment."

Dourish and Bell [3] reversed this assumption of a seamless world, and instead took it to be messy and complex, and that furthermore such seamfulness should be seen as a potential resource rather than as a problem to overcome: "The rhetoric of seamlessness is often opposed to the inherently fragmented nature of social and cultural encounters with spaces; we need to be able to understand how UbiComp might support rather than erase these distinctions." They programmatically called for design that finds opportunities within, rather than resolutions for such seams, highlighting and sustaining the "messiness of everyday life" as a central component. For Dourish and Bell [3], it was less about becoming invisible and instead about becoming mundane, describing ubiquitous computing devices as "highly present, visible, and branded, but perhaps still unremarkable." Drawing on Star and Bowker's [7] investigations of infrastructure and classification work, Bell and Dourish [3] noted that while a common ideal for infrastructure is ease and invisibility, in practice infrastructures are often visible through breakdown, through efforts to modify and adapt them, or through local solutions to interconnect them. As Star wrote, 'For the person in the wheelchair, the stairs and door jamb in front of a building are not seamless subtenders of use, but barriers. One person's infrastructure is another's difficulty" [44].

In a similar vein, Vertesi [47] brought the concept of seamfulness to STS and infrastructure studies. Less focused on design, and more akin to Dourish and Bell's formulation of a seamful world, Vertesi's conception of

infrastructures was *of a seamful space*. She illustrated the concept with an exemplary case drawn from her fieldwork at a NASA facility in Spain: Hidden behind desks and filing cabinets, she found the tangled wires of a power converter, transforming the American standard electric grid into a Spanish one. The NASA facility itself operated on the American standard, converting the power it drew from the Spanish grid for the scientific instrumentation that inhabited the NASA facility designed for the US. But local Spaniards working at the facility had, in turn, sought to convert that power back to the Spanish standard that powered their phones and computers. In this multi-layered and nested infrastructure what is seamful and what is seamless? Through great effort, a Spanish power source had been converted to an American one for an entire facility. Once completed, this work faded into the background as a stable American standard power infrastructure; but not for those who had sought to make their own local Spanish devices work once again. Much like Star [44] asserted for infrastructure more generally, seamfulness and seamlessness are a relational property: what is easy for one is a challenge for someone else and, in turn, the everyday work of another.

It is, in part, through Vertesi's work that the concept of seamlessness has reached a broader audience than CHI/CSCW/UbiComp, with influences in communication and human geography. In turn, Vertesi's formulations quickly returned to CHI, for example with Dailey and Starbird [17] characterizing "social media seamsters" who assemble heterogeneous, on-the-fly communication networks to manage local disasters. Employing the concept as it had been interpreted by Vertesi for the STS community, Dailey and Star returned it to the CHI community in this new formulation.

The specific language of seamfulness is relatively new for infrastructure studies and STS, but the gist of the matter — the revelations and concealments of human and technological action, and their relationship to agency — are longstanding themes for these fields. We have already discussed concepts such as infrastructure, but similar themes are addressed through terms such as 'black boxing, 'interpretive flexibility', 'technological closure', and 'invisible work'.

In their classic studies of urban infrastructure, Graham and Marvin [22] painted a long historical picture, crafting two periodizations of "infrastructural modernism" (roughly 1800-1960) followed by "infrastructural splintering". Infrastructural modernism bears striking similarities to seamlessness, which Graham and Marvin [22] characterized as "rationally planned, systematically rolled out through the urban fabric" and integrated into a "relatively standardized functioning whole." Iconic projects developed under such views include the razing of downtown Paris in vast plans for the "regularisation of the city through standardised, integrated networked infrastructures linked seamlessly", or the wholesale invention of the new capital of Brasil, Brasilia, as a "clean tablecloth […] designed from the ground up, according to an elaborate and unified plan", or the homogenous grid pattern of city development exemplified by Manhattan's numbered streets and avenues. Such street systems are seamlessly extensible in the face of growth, and by proceeding in a predictable arrangement can be easily navigated by driver and pedestrian alike. Both Graham and Marvin [22], as well as Scott [40], argue that such goals for seamless urban infrastructure worked its way into the ranks of urban planning, adopted as an ideal in theory and practice for both developed and developing nations.

Much like the advocates of seamlessness, infrastructural modernists were not villainous (for the most part). Rather, they drew on a vision of a public good that sought to democratize access to infrastructure (roads, water, communication) by developing it through a common vision of a shared humanity. Undoubtedly, some part of this vision has proven successful –for instance, the positive effects of infrastructural modernism in public health are apparent, even if uneven. But critics have drawn attention to the systematic troubles of the modernist ideal: the reconstructed downtown Paris, once a working-class neighborhood, become an enclave of wealth; the gleaming city of Brasilia made no room for the very workers who had built it; the extensible streets of Manhattan are, today, clogged with traffic.

In Graham and Marvin's tale, infrastructural modernism has been followed by splintering infrastructure, where "infrastructure networks are being reproblematised and (unevenly) brought back into view as major foci of debate, renegotiation and reconstruction within contemporary cities." In part, the forces driving such splintering are felicitous, such as women's movements and disability rights groups that sought to disassemble 'one size fits all' models of the public good. Such benefits parallel those that advocates of seamfulness have tended to highlight. But, in part, such splintering has also proven unfortunate. For example, recent decades have witnessed the disassembly and privatization of what were once public infrastructures of communication, transportation, and even neighborhoods (i.e. gated communities), creating what Graham and Marvin call

"infrastructural enclaves" of wealth and seamless living, surrounded by public decay: e.g., "New technologies are widely being adopted to allow favoured, rich and highly mobile travelers to pass seamlessly and quickly through ports, airports, and rail terminals, whilst other passengers face traditional, and in many cases intensifying, scrutiny." Different than, but still akin to its modernist predecessors, the benefits of tailored infrastructure and heightened attention to human difference has proven to be unevenly distributed, often organized around the classical societal cleavages of wealth, race, and moral marginality.

Such cautionary tales may serve as a warning to the advocates of seamfulness, for a big picture question to ask is who are the most likely wide-scale beneficiaries of the specialized, tailored, and attentive design practices that seamfulness calls for? When the spirit of seamful design leaves the experimental enclaves of academic research, how will it fare in spaces that structurally prioritize scalability, profit, or consumption?

Designers seeking case studies may thus find value in these detailed ethnographic and historical accounts, or in some of the theoretical concepts developed for understanding the varieties of visibility, invisibility, uncertainty and appropriation, and temporality. Similarly, STS and infrastructure studies scholars have sought analytical methods for revealing the operations of technology and people that are otherwise concealed by seamless, black boxed, or closed systems, such as infrastructural inversion, seeking breakdowns or finding master narratives. In the next section we return to the question of design to collate the 'tricks of the trade' that designers and analysts have developed, and offer these as part of the toolbox of seamful and seamless design.

4 DISCUSSION: TECHNIQUES FOR DESIGNERLY SEAMS

In this section, we return to the question of design, and present tools for working at the seams, creating seams, illuminating forgotten or neglected seams, and assessing when to conceal seams. As we showed in our review of the literature, the major themes revolve around in/visibility, un/certainty and appropriation, and the role of history in designing for the present. We treat each theme in turn.

While the majority of papers citing seamful design as a strategy for overcoming the black-boxing of seamlessness have focused on revealing disconnection in spatial relations (i.e. network connectivity breakdown over an aerial map), they have also centered around visually representing seams. The decision to reveal is based on countering the assumption that all users will desire constant connection to the network. On the contrary, users may have a variety of reasons for preferring to be in a space that is largely disconnected. For example, when paying per GB of data transmission, it behooves the user to more accurately inspect how much data is being "seamlessly" uploaded to and downloaded from their device(s). This questions the assumption that constant connection and seamless integration with applications is the ideal, and rather, illustrates how the concealing of data usage is revealed in other potentially dubious ways (e.g. with a throttled Internet connection or a high monthly bill). As such, it is always a question of not only what to reveal, but *how and when* to reveal.

The following section offers techniques for designing with and around seams: socially, technically, spatially, and temporally.

4.1 Becoming Seamless

To be seamless does not mean to be invisible, but to be compatible, mundane, interoperable. These are desirable interactional virtues in many circumstances. But in other circumstances they may be undesirable, such as for facilitating repair in the face of breakdown, for managing the circulation of too easily portable private data, or any number of additional contingent tasks. As such, there are tensions that pull at the threads of every seamless system. Similarly, central to seamful design is revelation – of error, of backgrounded tasks, of incompatible systems – but there is no system that is wholly revealing, wholly configurable for appropriation. Such issues speak to the challenge of design, which must offer configurability to local circumstances while simultaneously presenting some form of parsimony.

Investigating breakdown has proven a valuable pathway for understanding both seamful and seamless design. Our review of the literature surfaced many instances in which (failed) efforts to make systems or information seamless resulted in a revelation. As we discussed, strategies for dealing with errors or uncertainties often involves paying close attention to breakdown, and sometimes even purposely trying to break systems to find the flaws. These tactics have been taken up in the information sciences, particularly those focused on archival work and data interoperability. While not explicitly called out as seamful, Pepe et al. [35] use the terms "knitting" and "fabric" to refer to designing for interoperability with regard to scientific data practices – again, there are themes of collaboration, open access or transparency, and reuse by other potentially unconsidered

users. Although Andersson [1] argues that "invisibility can be seen as a measurement of seamlessness", we can see that it can also be used as a measurement of what is disruptive, uncertain, or in need of attention.

While Weiser [48] set the tall task of designing individual tools to maintain their identity while allowing for emergent interaction, many who followed forgot that compatibility can be just as important as customizability, seeing only the virtues of the latter. These themes and values surface in data scientific work as well. For example, Pepe et al. [35] write that the shared data model they propose "will allow objects to preserve their internal formats and languages, yet providing an intelligent account of the processes, tools, and resources involved in the generation of the object itself" (p. 6). Their work falls in line with a burgeoning interest in data practices of scientific research—more specifically, around making data more reproducible, interoperable, and commensurable, or otherwise, seamless [37]. Debates around interoperability and reproducibility mirror previous discussions among UbiComp researchers about when to reveal, what information to preserve, when to standardize, and when to allow for flexibility, and provide ground for exploring how breakdown might be leveraged as a design technique for surfacing the invisible or revealing deeper complexity.

4.2 Designing for Adaptation, Reuse, and Appropriation

Early CHI research mitigated seams by creating systems that had awareness of seams built into them [33]. However, later work explored ways that designers can utilize seams to better understand the user. Rather than concealing seams, the focus shifted to revealing seams that users can accommodate or appropriate as a tool for understanding often black-boxed phenomena (e.g., algorithms) [19]. This approach has also been leveraged by designers to understand user behavior and local knowledge. However, there are many uses for concealing as well. For example, to make sense of large amounts of data, some concealing and reduction are necessary.

Rather than following the invisible work of system designers, Singh and Jackson [2] note the importance of documenting "the invisible work demanded of users at the seams as they seek to overcome the barriers that partial and selective inclusion, even of putatively 'universal' systems, periodically throws up." Designing for reuse or re-appropriation requires designing for some kind of general user. While seamful theorists certainly would not condone the image of a "general user", too much context is just noise. As a designer, the handhold one puts in place should be informed by an understanding of what types of uncertainty one wants to exploit: uncertainty in user knowledge, uncertainty in user environment, uncertainty of user preference, or other emergent properties that might require more speculative approaches.

Chalmers and Galani [14] envisioned seamful design as enabling the user "to selectively focus on or reveal [seams] when the task is to understand or even change the infrastructure." This, however, requires understanding what has remained tacit. It is not uncertainties, errors, or seams that are disruptive to seamless integrations, but that uncertainties have been rendered unavailable in everyday interaction. One example of seamless integration is middleware, which allows developers to access "high-level information based on error prone sensor input" [29]. Jensen [29] argued for a device that would allow developers to switch between seamless and seamful interaction, or in other words, a system adaptive to the user's on-demand requests. But to design an adaptive system requires first understanding how users adapt, which in turn requires making explicit what is embodied or implicit.

A recurrent example in the literature has been that of riding a bicycle or driving a car. These practical, skillful tasks become backgrounded as the artifact becomes more a part of ourselves, an embodied knowledge. As a researcher, it is crucial to learn what is embodied to the user, or what is technologically backgrounded. While initially Weiser equated cognitive background with technological delegation, he later reconsidered [55]: "The difference between something being effectively invisible because it is being processed below conscious thought and something being managed for us (e.g., by a computerized agent) is profound." Cognitivist formulations cast technological delegation as akin to that which occurs in the human mind, while interactionist formulations cast technological delegation as their own distinct beast. From this perspective, the backgrounded work of an algorithm is unlike that of distal tacit knowledge, and, revealing how an algorithm has transformed data is unlike cogitation. The designer must then ask, what specific kind of backgrounding has occurred, and what kind of interaction may be of use revealing it. In some instances, the designer may want to sustain that background; in others, they may want to bring it to the surface to better understand design solutions.

4.3 Temporality and Designing with the Past

Our review found that while much of the literature characterizes seamful and seamless as a way of dealing with heterogeneous data and scenarios – spatially,

temporally, and technologically – the majority of the research to date has focused on spatial contexts rather than temporal. Much of the work on seamful design has taken as their exemplar working across digital and practical divides –e.g., screens and papers on a desk, or augmented reality gaming – or, focused on working across heterogeneous networked systems – e.g., uneven WiFi or cell-phone coverage and incompatible file formats. Always present, but with far less research, has been working across time. Through our review of the seamful/less literature, we found a lack of focus on users in situated contexts seeking to interact with some facet of their own past actions, other's backgrounded organizational actions, or technologically delegated actions (such as those evoked by "algorithms" or "infrastructure"). This opens a fruitful opportunity for understanding and designing for temporal seamfulness.

Drawing on the case of ecological researchers, Inman and Ribes [26] prototyped a visual technique for bringing the past of ecologists' data transformations to the surface by using archival documents to rebuild their history of data transformations. Rather than invisible or hidden, Inman and Ribes [26] sought to create a seamful representation of data interoperability so that ecologists could revisit the decisions they had made (and why) for transforming their 'raw data'. Such goals dovetail with recent concerns about the reproducibility of scientific work, which is at times concerned with whether data transformations may be at odds with goals for faithful scientific inquiry.

But a wholly seamful approach to such data genealogies would be nonsensical. For instance, for ecological datasets that span decades, the number of transformations to instruments, routines of data and specimen collection, efforts to calibrate and past efforts to standardize, is vast and overwhelming. Presenting even a fragment of such an immense history to a working ecologist – with a research question in hand – would present a highly undesirable seam and hinder their core goal of investigating ecological phenomena.

As such, seamful representations require work to situate such a tool in their settings of use. It requires looking for the themes that cut across different uses of data, seeking an understanding in questions such as: what past transformations to data are relevant to current research? What level of granularity of understanding past transformations is valuable, and what is too much? When does drawing back to the institutional or cultural memory prove insightful, and when is it intrusive to the task at hand? This type of research benefits from a situated understanding of current practices to inform possibilities for future appropriations of data genealogies. More broadly, understanding technological interaction histories or historically delegated algorithmic decision making seems an interesting and fruitful avenue for future seamful research.

5 CONCLUSION

In this literature review, we tracked what we initially characterized as a debate, originating in UbiComp, quickly taken up beyond, in which advocates of seamful design cast seamlessness as a longstanding tacit design virtue. However, this story has been less of a debate, per se, and instead more accurately characterized as a mutual conceptual articulation of the seamful and seamless concepts. Overall, at least in the literature, seamfulness has largely been well received, and there has been, as of yet, no unyielding champion of seamlessness that has risen to its defense.

The seamful approach has called out seamlessness as having been an implicit value; however, through our readings of the literature, it is clear that seamfulness too has been an implicit value and has operated alongside seamlessness, even while acting as a subordinated virtue. The discussion we have tracked has led to clearer mutual articulation of the two design approaches, breathing new life into the perennial tensions between visibility and invisibility, foreground and background, uncertainty and design for appropriation, and novel development cast against challenges of legacy infrastructure. One outcome of the debate is that it is now easier to consider seamfulness a complement to seamlessness, rather than a second-order design option. Discussions about seamful strategies and design methods thus place at center stage concerns about user's understanding of the technology, ease of use and local tailoring, and their potential context of use, even while tidy, accessible, coherent seamlessness remains a possible consideration for good design.

Rather than a debate, then, we have largely told the story of a conceptual evolution that occurred through a series of talks and publications given by Mark Weiser, and then theoretically elaborated across the years by colleagues, intellectual descendants, design adherents, and so on. Weiser articulated that which had largely operated as a longstanding design virtue; he did not oppose it though, rather, through his research, he furthered seamlessness (for example as ambient or calm technology). But only shortly thereafter he offered what we have argued is its complement, seamfulness.

Initially, perhaps, he formulated both concepts through a unique mix of cognitive science and phenomenological philosophy: somehow Herb Simon, while also Michael Polanyi; both cognitive load and tacit knowledge. But later, drawing on sociological studies occurring in his own back yard [52], Weiser began casting the issue through more interactionist formulations of contested human action and human-machine relations.

Chalmers et al. [14] particularly picked up, and through their scholarly work preserved, what was perhaps Weiser's synthesis phrase "beautiful seams". It is a phrase that seems to capture both the spirit of user-friendly, coherent design emphasized by seamlessness and the heterogeneity, contingency, and appropriability of seamful design. We began this review essay with the epigraph *"If something has been taken over for me, is there a presentation of what has been taken over that I can bring to the fore whenever I like, including retroactively? – Weiser [50].* The example may seem mundane, as with many cases of research on interface, but we consider it a curious one to think through. Is this a wishful expression for seamless utility or for seamful interaction? The question seems ill-formed, or perhaps moot. But apply the phrase 'beautiful seams' to it, and it seems a little jewel of an example: a user, set on a task, is asking, what has the system taken over, and how did it do it? Perhaps it is an algorithm or a data visualization, and the scientist-user is asking, how have these data been processed to give me this particular finding? Perhaps it is a social media user, curious as to why this or that posting or advertisement was presented to them. Or, perhaps it is an organizational actor seeking accountability for delegated actions.

How, in a particular context such a tool can be considered to be a beautiful seam, cannot be resolved in the abstract, but only through a design practice that considers its situated use, local balancing acts, and the complex interactions that make up human action. The ideal of a beautiful seam perhaps suggests that the virtues of seamlessness (and the findings of research inspired by that concept) can still be of use, even in the most contextually situated design for appropriation.

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