Towards Habitable Bits: Digitizing the Built Environment

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ABSTRACT
Recently, there has been a growing number of research efforts aimed at the *digitization of architectural space*. Whereas conventional attempts at integrating digital technology into architectural space have typically viewed architecture as an inflexible backdrop onto which layers of digital devices/services/information can be *overlaid*, the newly emerging efforts instead strive to *inject architecture itself* with the distinct plasticity of digital bits. In this paper, we will first provide a review of this nascent body of work, weaving together the disparate streaks of technical development into a consilient research trajectory that can be interpreted as a modern-day extension to Weiser's original vision of Ubiquitous Computing. Next we turn to the two decades' worth of criticisms raised against the UbiComp ideal, to expose what perspectives are missing from the fledgling efforts, and to identify the roles the HCI community can play in shaping the future of this promising line of work.

Author Keywords
Habitable bits; habitable user interfaces (HUIs); synthetic space; ubiquitous computing; responsive architecture; augmented architecture; printable architecture.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous.

INTRODUCTION
Despite its publication in a popular magazine as opposed to a scholarly journal, "The Computer for the 21st Century"—the famed essay by Mark Weiser [61] in which he introduced his vision of Ubiquitous Computing—has firmly emerged as one of the most impactful writings in computer science of the past several decades. The level of accuracy with which Weiser had anticipated future technical advances is uncanny; the popular notion of an ongoing shift towards a *post-PC era* is all but an exact facsimile of Weiser's words, with only small differences in terminology (Weiser used *tabs*, *pads* and *boards* instead of *smartphones*, *tablets* and *interactive surfaces*). The degree to which Weiser's influence can be felt both in and outside academia is a testament to the power of academic writing to generate profound societal impact.

Whereas many of the commentaries on Weiser's writings [51] have focused on his idea of "invisible computing" (the notion that interaction with computers should be as seamless and undemanding as writing on paper), here we would like to instead bring attention to "embodied virtuality"—another of the varied (but interconnected) themes touched on in his epochal essay—i.e., the idea that the distinctive properties of digital bits should cease to be accessible only within the PC, and instead be made to permeate across the full extent of the physical environment. The concept is eloquently expressed in the following short sentence from Weiser's essay (note the unique usage of the term *virtuality* here):

> The "virtuality" of computer-readable data—all the different ways in which it can be altered, processed and analyzed—is brought into the physical world.

A prescient statement, that more or less summarizes the myriad HCI innovations over the past 23 years. Indeed, the various research concepts/initiatives—e.g., mobile computing, tangible user interfaces, ambient displays, augmented reality, surface/tabletop computing, to name a few—have all contributed to the steady injection of "virtuality" into the physical world. At a quick glance, it appears that we have already turned embodied virtuality into an indisputable reality.

However, on close inspection we find that instead of virtuality fully permeating throughout the physical world, these intense developments have culminated to form multiple auxiliary layers of digital devices/services/information atop a primarily inert background of *static architecture*, i.e., the traditional built environment composed of ceilings, walls, floors and windows (Figure 1). Digital plasticity flourishes, but only on the auxiliary layers; it seldom (if ever) invades the architectural layer, which is largely assumed as invariant. This attitude is implicit but prevalent. A typical *augmented reality* city guide app for smartphones merely overlays panels and bubbles onto an otherwise unaltered city scenery, and a typical *interactive wall* in corporate offices only permits digital interaction with the 2D graphical contents displayed on its limited, stationary surface. For the most part, the pursuit of embodied virtuality so far has stayed one step short of *digitizing the built environment*.

The Achilles' heel of this attitude is that architecture is by no means a neutral, uninvolved background layer. Studies in environmental psychology [12, 55] have shown that our actions, thoughts and even emotional states are strongly influenced by

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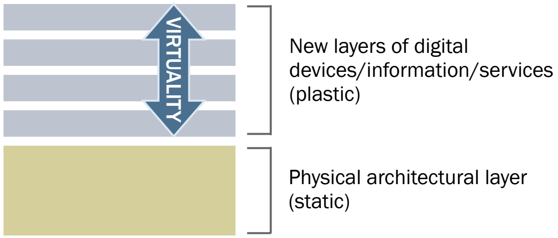

Figure 1. "Virtuality" only spreads within the new, auxiliary layers.

the design of the environment, both indoors and outdoors. To use an example rooted in our day-to-day lives as researchers, we will struggle to write papers, even if provided with a (hypothetical) perfect word processing software on a perfect laptop/tablet, if the environment is not conducive to such activities. (This manuscript was mostly written at a greatly conducive café in Berlin; trying to write at the local Thai joint never yielded quite as good results.) Architecture, far from being an impartial bystander, acts in fact as an active and potent manipulator of myriad human behavior—including our interactions with digital technologies [18].

What we are now witnessing is the spread of virtuality strictly under the reins of architecture. For us to truly infuse the benefits of virtuality throughout the physical world, architectural space itself will need to be digitized, i.e., imbued with the distinctive properties of digital bits (plasticity, interactivity, ease of modification/duplication/distribution, etc.).

As we will illustrate in this paper, there are emerging, but still largely isolated, efforts targeting precisely that goal. Though so far the HCI community has generally been reluctant to deal directly with the design of architectural space, we believe that this nascent group of efforts can act as harbingers of an exciting research direction, that offers the community an opportunity to further extend Weiser's vision for the coming decades. While the complete digitization of the built environment (Figure 2) will likely elude us even in the distant future, the range of technical approaches, with further development, may bring us ever closer to this seemingly improbable goal.

The paper will begin with an in-depth review of the emerging efforts (which exist primarily in HCI/CS research but also in diverse fields including Architecture and the Arts), categorizing them into the following three key approaches: *responsive architecture*, *augmented architecture* and *printable architecture*. Next, we turn to the wealth of commentaries on Weiser's ideas and their aftereffects that have arisen in the past 23 years both within and outside of the HCI community, using them to reveal missing perspectives in the future vision (*proximate future* [11]) underlying the newly emerging efforts. Finally, we will conclude by discussing what roles HCI research can play in steering and further developing this line of work.

The paper's primary contributions are: (1) weaving together a wide range of disparate, emerging technical efforts into a coherent narrative that extends Weiser's vision, offering a common framework/language within which relevant works can be couched, and (2) formulating a critique of said narrative that draws on criticisms raised against the UbiComp ideal, deriving from which a list of possible future contributions the HCI community can make in this domain. While the paper's scope may on surface appear to be overly broad and eclectic, discussions are held together by a consistent interest in the closer integration of digital technology and the physical world—a topic of central relevance to the HCI community.

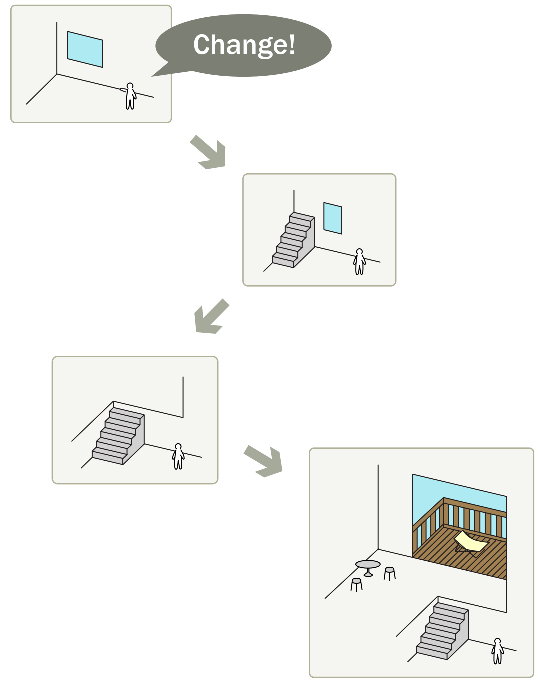

Figure 2. In a hypothetical, "fully-digitized" architectural space, transforming the environment will be as easy as changing the desktop wallpaper on a modern-day PC.

HABITABLE BITS, SYNTHETIC SPACE

To be fair, humans already possess a number of technologies that manipulate space, which we use on a daily basis. Calling someone on the phone can instantly *compress space*, portable MP3 players effectively surround us with *auditory walls*, and airbnb enables us to freely convert our homes into hotels, etc. Combine this with the wealth of published research on tangible user interfaces, smart homes, urban informatics, etc., and we can easily see that the entire scope of *space-altering* technologies is practically infinite, and has been growing long before the arrival of the nascent efforts that are the central topic of this paper. The new efforts, however, possess the following traits that set them apart from their precedents:

- Builds upon a clear awareness of the power of architecture to influence human behavior and psychology
- Demonstrates an intention to explicitly *curb, control or enhance* the said power of architecture
- Accomplishes the above via digital manipulation of one or more of the physical properties of architectural space

The range of technologies that possess these traits is diverse. As should become clear later in this section as we list related

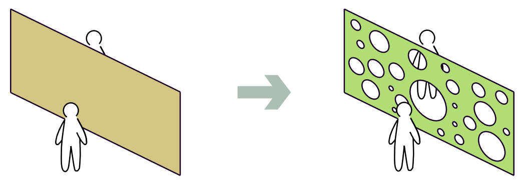

Figure 3. Responsive architecture. In this relatively small-scale example, the responsive wall's color changes to green and apertures appear on its surface, allowing passersby to see through to the other side.

work, we are not anticipating an imminent birth of some kind of a hyper-futuristic wonderland, where entire buildings/cities are made out of ceaselessly shapeshifting programmable matter. Rather, what we are observing is a steady pace of innovations occurring in heterogeneous technical domains, that will in time collectively chip away at the longstanding stability of the architectural environment. Ultimately, the ever-increasing latitude with which we can alter our surroundings will lead to the experience that we are living within a world built of "habitable" bits—or, to use a term introduced in a previous publication, living within "synthetic" space [57].

Within prior work, we have identified three key technical approaches—*responsive*, *augmented* and *printable architecture*, respectably—which we predict to serve as the main drivers of the coming digitization of architectural space. Below, we will provide a review of notable efforts belonging to each of these technical approaches.

Responsive Architecture

Responsive architecture refers to a class of architectural structures/environments, which can dynamically alter their shapes and/or appearances using kinetic transformation mechanisms, RGB displays, etc. The terminology is still not entirely fixed, and alternative names denoting similar concepts exist such as *interactive architecture* [23] and *kinetic architecture* [67] (although the latter may more appropriately be considered a subcategory due to its exclusive focus on kinetic transformation). In both academia and architectural practice, the label does not apply to input-only systems (for example wide deployment of sensors, surveillance cameras, etc.) and requires the existence of some form of digital output capability, often involving dynamic adaptation to input (Figure 3).

Responsive architecture as a research category has only begun to receive a serious look in the last few years in the academic HCI community [17, 26]. Hence the list of precedents is still short, and mostly comprises sporadic works presented outside the main tracks of top conferences [33]. The concept has long been of interest to architects, however, and there already exist examples of commercially successful applications such as revolving restaurants, retractable stadium roofs, *media facades* [63], etc. Although due to the immense cost (especially when involving mechanical transformations; fantastical visions like Archigram's *Walking City* [16] will likely remain fantasies for the foreseeable future) such constructions are seldom seen in residential or low-budget commercial projects, innovations in digital design/prototyping tools (e.g., *Grasshopper*) are rapidly dismantling many of the traditional hurdles associated with this domain. Hence it may not be irrational to expect growing usage of various responsive architecture in everyday environments, albeit at scales smaller than entire buildings—e.g., kinetic facades [34], adaptive furniture [36, 60], etc. This may be aided by the recent fascination within HCI with shapeshifting user interfaces [48], which can potentially yield new technologies applicable to the design of such structures.

Despite not making much inroads into responsive architecture *per se*, the HCI community has neither been oblivious nor indifferent to the capacity of architectural space to steer human behavior and provide overarching context to interactions [18]. Early works on media spaces [13] and ambient interfaces [66] are clearly built on a recognition of the power of architecture, for example. However, as has been the case with most efforts in HCI research, they have primarily been concerned with designing systems to be installed *atop* the architectural environment, instead of attempting to *actuate architecture itself*. Out of the mainstream topics pursued in HCI research, *interactive surfaces* may perhaps have the most to share (in both concept and technology) with responsive architecture. Interactive surfaces—i.e., architectural surfaces with digital I/O capabilities—have long been a staple in HCI research, having their roots in Weisers *boards*, and highlighted by Ishii [29] as one of the key components of *Tangible Bits*.

Seeing how research on interactive surfaces has evolved in recent years, we can identify three ways in which this area has progressively turned "architectural" in its concerns.

The first is the expansion in scale. From Augmented Surfaces [50] to Multitoe [7] and LightSpace [65], interactive surfaces have steadily increased their area of coverage to entire rooms, making the whiteboard-sized *boards* look minuscule in comparison. The quantitative growth in scale has brought forth a qualitative change in topology; interactive surfaces no longer coexist with users *as equal entities* inside the same room, but instead *enclose* users, in the same manner as architecture. The second is the diversification of context. While early works on interactive surfaces installed and studied them mainly in laboratory settings, many recent works investigate their use in everyday environments, such as homes [37] and streets [21, 47] This indicates how the technology has matured from its initial status as a novelty for research labs to a potentially commonplace constituent of the future built environment. The third is the evolution of interaction techniques. Humble touchscreens have since been joined by gesture input [42] and *proxemic interaction* [10]—a driving force behind this development is the recognition that as interactive surfaces begin to *enclose* users, we could no longer assume that users will adopt a fixed pose/position/distance when engaging with these surfaces.

The three developments all point to a future where interactive surfaces no longer are confined within perceivable boundaries and begin to permeate across the environment; we will not interact with them in the traditional sense, but will instead start to *inhabit* them. Put another way, research on interactive surfaces is proceeding along a path that an eventual collision and intermixing with responsive architecture seems inevitable.

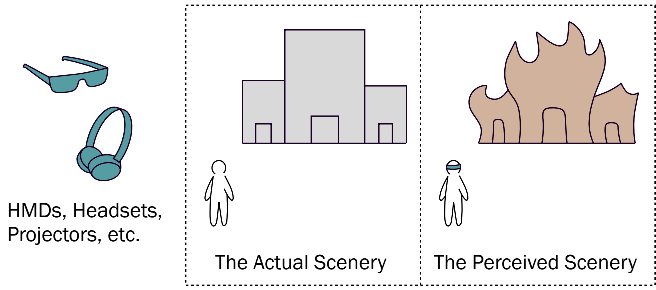

Figure 4. Augmented architecture. Augmented reality technology is used to filter the user's perception of space, offering the experience of a "digitized" architectural environment. Since the effects are illusory transformations need not follow real-world constraints, e.g., the laws of physics.

Augmented Architecture

Augmented architecture does not involve actual technical interventions to architecture itself; rather, the label represents a class of technologies that employ *augmented reality* to "filter" users' perceptions of the surrounding built environment, producing *equivalent* experiences of digitized architectural space (Figure 4). While one may rightfully argue that such technologies (that exert no power over architecture per se) should be discounted by definition when considering attempts at digitizing architectural space, in light of the possibly wide adoption of augmented reality technologies and the key roles they may come to play in shaping our future spatial experiences, we instead deem it myopic not to include them in our discussions. (However, we do exclude *virtual reality* from our discussions, keeping in line with Weiser's positioning of the technology as being diametrically opposed in principle to UbiComp.)

It may be possible to say that the entire premise of augmented reality involves the digitization of the environment. However, within prior work in this field we observe a curious reluctance towards actively manipulating architecture using this technology. (We gave an example earlier in this paper; a typical augmented reality app for mobile devices merely overlays panels/bubbles over an otherwise unaltered city landscape.) This reluctance has historical roots. Early works on augmented reality [20, 49], owing to technical limitations at the times, could only display simple (by today's standards) graphics on top of an unaltered live video feed. The metaphor has stuck, and today many augmented reality systems adhere to it despite the fact that technical advances have made real-time image processing feasible, even on mobile devices. Recently we are beginning to see a shift, however. Using techniques from diminished reality [43], ClayVision [59] has demonstrated how the field can move beyond mere overlays of virtual signage, presenting users with the capacity to grow, transform and remove buildings with ease. With fast, robust computer vision libraries for mobile platforms becoming more widely available, we expect similar efforts (that effectively inject *virtuality* into the architectural layer, although the transformations are illusory) to increase in number in the next several years. Future developments may lead to less cumbersome hardware (lightweight glasses, etc.), and higher fidelity that will further blur the line between external reality and the illusory effects.

Bachelard [9] argues that our experience of space is a holistic one that involves multiple sensory channels. If so, augmented architecture must cater to a wide range of modalities not limited to vision—otherwise the experience offered would not be felt as anything more than a superficial veneer. Although still sporadic, in HCI we can see a growing number of works that address this concern. For example, Weightless Wall [58] uses custom headsets to simulate sound-blocking walls that can be erected anywhere in a room, which is proposed as a key component of a new office design where workers can freely erect, delete or modify walls to suit their tasks at hand. Haptic augmentation is being studied as well; CabBoots [24] and Gilded Gait [56] are both footwear-shaped devices that can mechanically alter sensations of ground shape/texture. However, even with such promising developments, it must be noted that it is highly unlikely that augmented architecture will ever be able to cater to the full range of human sensation, which is a fundamental limitation of the approach. (We will later list and compare the respective advantages and drawbacks of the three key technical approaches.)

Projection-based (or *spatial*) augmented reality represents another important variation of augmented architecture technology. While the use of projection has a long history in HCI (being used to render interactive surfaces for example), the growing availability of low-cost depth sensors has made projection onto large, complex (non-planar) environments easier, which is evident in works such as IllumiRoom [30] where the living room is turned into an extension of the TV screen. The use of mobile/wearable projectors for spatial augmentation has been investigated as well [52, 45]—which may yield another viable approach to augmented architecture, provided that power outputs of compact projectors see sufficient increases.

While the most cutting-edge technical efforts in this area are still found predominantly in HCI/CS research, augmented reality has also attracted much attention in the fields of architecture and the arts, leading to large-scale implementations rarely seen in laboratory research. One example is the *N Building* [4] in Tokyo, whose front facade constitutes a giant QR code (fiducial marker) that allows pedestrians to see virtual animations by looking at the building through smartphone cameras. Spatial augmented reality has been widely adopted as well, in the form of *projection mapping* onto buildings which has become a popular attraction throughout the world.

Printable Architecture

Printable architecture (Figure 5) refers to a class of technologies that can automatically "print out" full-scale architectural structures from digital files, using techniques such as additive manufacturing (i.e., *3D printing*). Compared to responsive or augmented architecture, these technologies operate at considerably slower time scales—thus they do not support instantaneous transformations of environments like that illustrated in Figure 2. (More precisely, they do not actually support transformations at all; structures can merely be replaced with newly printed ones.) Even with such limitations, however, we believe the advent of printable architecture to be a key development towards the digitization of architectural space, due to its potential to bring the high degree and ease of consumer-level

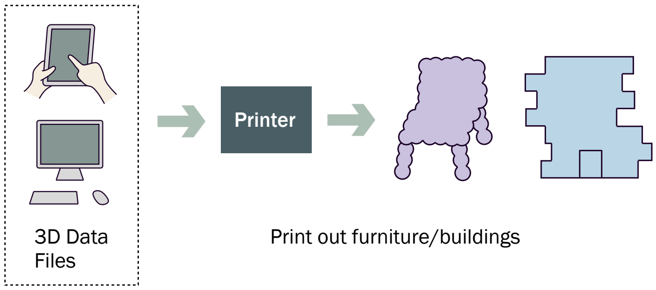

Figure 5. Printable architecture. Furniture/buildings are digitally fabricated from 3D data files, that can be newly created by users, downloaded from online repositories, etc.

customization—a characteristic property of digital media—to the design of architectural space.

Since the area is in an even earlier phase of development than responsive or augmented architecture, precedents are still few in number and also highly experimental in nature. So far there have been no notable efforts within HCI research that deal directly with printable architecture, and most technical developments are seen instead in the fields of architectural design and civil/environmental engineering. Printing out entire *habitable* buildings, which may well be the holy grail of printable architecture, is being attempted but existing efforts (e.g., D-Shape [2], Contour Crafting [35]) have not reached a level where we can expect practical usage in any short-term future. An alternative approach is to digitally fabricate smaller components, that are later assembled manually to produce the final design; this is the method adopted in 3D Print Canal House [1] and in some artistic installations [3]. At the furniture scale, 3D printing is already fully feasible, and one can find many products on the market fabricated using this technology, as well as directions/files to print one's own on websites (such as *Instructables*) for DIY hobbyists with access to digital fabrication facilities. Other, seemingly far-fetched approaches for automatic construction are also being investigated, for example *flight assembled architecture* [25] which relies on an army of quadcopter drones to construct brick buildings.

Overall, though printing out entire residential houses or apartments still seems to fall into the realm of science fiction—and appears to stay that way, in dense city centers at least—printing out smaller-scale structures (e.g., room interior, furniture) is quickly becoming viable. Perhaps a sensible prediction for the role of printable architecture in the short-term future may be that it will *complement*, and not *replace*, existing construction technologies, that still hold substantial leads in areas such as structural integrity, material choices, etc.

In HCI, while attention towards printing technology itself has surged in the last few years, the main concern has been developing techniques for printing *functional* objects such as optics [64] and electronics [31]—which likely are not directly applicable to printable architecture (unless we are printing responsive architecture, which may happen in the future). However, there is a respectable line of work on digital design tools, and a wide range of techniques have been developed [28, 54] over the years aimed at making 3D design more accessible and intuitive for non-professional users. While such works may not count as contributions to printing technology itself, they nevertheless will constitute an indispensable part of the printable architecture *ecosystem*.

Adherence to Architectural Conventions

Besides relying on straightforward technical classifications as above, another way to categorize and make sense of the range of technologies contributing to the digitization of the built environment is to look at their different attitudes toward our preconceived notions of architectural space—i.e., the timeworn, largely pan-cultural (in industrialized regions at least) image of rationally delineated space, composed of floors, walls, ceilings and windows.

We use the term *conservative* to refer to technologies that inject digital properties into architectural space, while still generally conforming to traditional ideas about the makeup of the built environment. Depending on the degree to which they adhere to traditional ideas, we further classify them into *literally conservative* and *metaphorically conservative* technologies.

Literally conservative technologies take a strictly traditionalist stance, faithfully retaining the "classic" experiential qualities of traditional architectural space. Responsive architecture that rely solely on kinetic transformation usually falls into this category; one good example is *Maison à Bordeaux*, designed by Rem Koolhaas [38], in which an embedded elevator moves the floor up and down within the house. Although each move of the elevator renews the spatial logic of the building, within each static state—i.e., when the elevator is standing still—the spatial experience is precisely that of a conventional architectural environment. A visitor may quite possibly not notice the dynamic capabilities of the building, until a transformation is actually observed or experienced. Printable architecture typically belongs to this category as well.

Such technologies are in contrast to those that are *metaphorically conservative*, i.e., technologies that introduce markedly foreign elements into the makeup of the environment, but are nevertheless designed to operate along traditional architectural metaphors. Many augmented architecture technologies belong to this category, as they are likely (even with future technical advances) incapable of offering *literal* experiences that operate on the entire spectrum of human sensation. For example, the sound-blocking virtual walls of Weightless Wall [58] are distinctly foreign elements not part of a conventional built environment, but the technology is still designed to have *metaphorical* similarity to real, physical walls.

In time, we can expect technologies to appear that act largely independent of conventional metaphors. We use the term *progressive* to refer to these yet hypothetical future technologies. In his essay, Weiser predicted a gradual adoption of UbiComp technologies, considering the adoptions of *tabs* and *pads* to be necessary conditions for the later adoption of *boards*. We expect a similarly stepwise process for the digitization of architectural space; *conservative* technologies will first provide the initial scaffolding, for the belated emergence of the more radical, *progressive* technologies.

	Responsive Architecture	Augmented Architecture	Printable Architecture
Offers Literal Experience	Yes	No	Yes
Range of Transformation	Moderate	Very High	High
Time Scale of Transformation	Instantaneous	Instantaneous	Slow
Cost	High	Low	High

Table 1. Comparison of the three key technical approaches.

Comparison of Technical Approaches

Table 1 shows the respective advantages and drawbacks of the three technical approaches we have discussed thus far.

Responsive and printable architecture both have the potential to offer *literal* (as defined earlier) experiences of architectural space. The capacity will likely be absent from the majority of augmented architecture systems, whose effects will predominantly operate on the user's sense of vision; while augmented reality glasses can make a smooth wall *look* bumpy, if the effect is merely visual it will still feel smooth when touched by hand. (In contrast, a responsive surface that can mechanically alter its texture [41] can be made to both look and feel rough.) Also, effects of (non-spatial) augmented architecture are only perceptible to those wearing the supported devices.

On the other hand, augmented architecture allows both immediate and wide-ranging modifications of environments; buildings can be made to wildly swing around as if they were made out of jelly [59]. Transformations of environments via printable architecture will not be as instantaneous, and those via responsive architecture will lack the high degree of freedom.

In terms of cost, augmented architecture will probably be the most reasonable, owing to its reliance on wearable or portable electronic devices. Costs of printable and responsive architecture will typically be higher, and will also be highly divergent depending on scale, choice of material, etc.

It is important to note that the three key technical approaches we have discussed had been identified based on existing work, and we do not rule out the possibility that other types of technologies will emerge that end up making larger contributions to the digitization of the built environment. In fact, we regard such scenarios as being entirely plausible—our opinion is that HCI and other related CS subfields have generally been hesitant to explore ideas that cross over with architectural design, which has thus far limited the types of technical contributions that could be made within this space.

THE IMPLIED FUTURE

We have now described the range of technical approaches that we expect to play primary, but not necessarily exclusive, roles in the coming digitization of the built environment. However, descriptions of individual technologies by themselves fail to give a holistic sense of what life could actually be like in such a future. Here, as Weiser had done in his original essay (albeit with a word of caution about the inevitably quixotic nature of such efforts), we would like to extrapolate from today's rudimentary fragments of *habitable bits* to provide a hypothetical scenario of everyday life, in a world where embodied virtuality has fully run its course.

In a tiny studio apartment in a dense city center, Sal awakens. She smells coffee—the array of sensors laid out under her 3D printed bed had detected her awakening, and promptly started the coffee machine. With mug in hand Sal glances at the wall, which flickers as if to say good morning, and begins to display various information such as news headlines, weather forecast, and her health status measured by the bed during her sleep.

Sal starts to prepare for work. She had recently moved to this town; as is typical here the apartment is old and cramped, but her newly printed interiors (complete with a small indoor garden) are optimized to make the most efficient use of space.

The office is roughly a 15-minute walk from Sal's apartment. From her bag Sal takes out her *glasses* and puts them on. Not that she has any problems with eyesight, but the glasses allow her (in addition to seeing her friends' status updates at the periphery of her vision) to customize the urban landscape to her liking. Several cafés on the street immediately begin glowing in different colors, indicating their levels of crowdedness. Sal enters the least crowded one, and soon comes out with a muffin in her hand.

Sal walks across a plaza, at the heart of which there is a large public monument emitting light in various bright colors. This is not an illusory effect created by the glasses—the light is actually being emitted, and its colors reflect the current mood of the city obtained by performing sentiment analysis on the citizens' public status updates. Looking at the bright colors, Sal surmises that many people are excited about the soccer match scheduled to take place later in the day.

Buildings around intersections appear translucent through the glasses. This lets Sal easily be aware of any cars/bicycles that may be heading in her direction when crossing streets. Multiple RGB/depth cameras (whose images are anonymized at the hardware level) are installed throughout intersections to make this possible. This is one of a range of technologies that have made streets—now busier than ever, due to diversified means of transportation—much safer for pedestrians/cyclists.

On the edge of the sidewalk, Sal notices a line of glowing tiles on the ground. She halts her walk and pays attention to them; suddenly lush trees emerge from the tiles' surfaces. The trees are not real, but are visualizations of the city's plans for lining its streets with trees. In this way, by using the glasses citizens can see and comment on their cities' design proposals. While this hasn't changed the messy nature of planning politics, the technology has given citizens an ever wider array of channels through which they can affect and take part in the process.

After passing by an interactive mural and a series of buildings adorned with 3D printed gardens, Sal arrives at the office. The floor is crowded—although telepresence systems are in place that now allow remote workers to communicate seamlessly as if they are working in the same room, the relative advantages of face-to-face communication have still not eroded, and thus many of Sal's colleagues make the conscious choice to physically commute to work. The office is of an open-plan design, largely devoid of walls other than those structurally necessary and several others made of *switchable glass*. Sal picks up her *headset* from her desk and puts them on; this, working together with her glasses, lets her create translucent, sound-blocking walls (whose effects are shared by all employees wearing the headsets) anywhere in this congested office. Feeling the need to concentrate as she reads through a technical document, Sal encircles herself with walls to temporarily isolate herself from the surrounding noise.

Sal hears someone knock on the virtual wall—it is Jon, a colleague with whom Sal has been working together on a project. After chatting briefly inside the wall, they decide to get some coffee and Sal deletes the wall. At the coffee machine the two bump into several other colleagues, and they all share updates on their respective projects. Above their heads, shapeshifting chandeliers offer enjoyment emitting soft, relaxing light.

Having finished her job for the day, Sal walks toward the station to meet her friend Mary; they had promised to go to dinner together. On her way is a park, where she can see children playing games on a brightly illuminated landscape—a projector system is installed in the park capable of rendering various games tailored to the number and ages of children on site. Sal sees children frantically jumping across what looks like stone platforms floating on a lava field.

Sal finds Mary; they hadn't yet decided on what or where they would like to eat. The two sync their glasses, so that they both see a similarly transformed city. Sal utters "*find restaurants*", and promptly all non-restaurant buildings turn into short, featureless gray blocks. Mary says "*I feel like Thai tonight*", and again a group of buildings promptly turn flat and nondescript. The respective heights of the remaining buildings reflect their average ratings on a restaurant review website. Sal adds "*I'm a bit short on money lately, I need to keep it under 30 dollars*", which leads to yet another batch of flat, gray blocks. The two head for the tallest remaining building in sight—i.e., the highest rated Thai restaurant within their budget—and enjoy their meal. The wholly 3D printed interiors of the restaurant makes them feel as if they are dining in an ancient Thai temple.

Having parted from Mary, Sal again walks across the plaza as she heads home. The monument is glowing in a sad, blue color, and has visibly shrunk in size compared to the morning—Sal guesses that their team has lost the soccer match.

Sal arrives home, takes a shower and then goes to sleep; when morning comes, the wall beside her bed will glow in a warm, orange light to gently wake her up.

Although the above scenario is mere speculation, the short vignette illustrates how simple extrapolation of emerging technologies hint at an impending drastic shift in our relationships with architectural space. The optimistic (one may say *techno-utopian*) tone is a reflection of the fact that these technologies are still in phases of early development, and their descriptions in literature tend to focus on elucidating seductive future possibilities in bold, graphic terms, rather than offering cautious reflections on their real-world feasibility or implications. For example, consider the following excerpt from [30]:

> When the game starts, the room magically transforms to look like a cartoon, matching the shading in the video game. The colors of the room become super-saturated and cartoon edges appear on your bookshelves. You come across an enemy in the game, and suddenly a streaking bullet flies towards your character and then out of the television.

Or this passage from [57], that gives off an even more techno-utopian ring:

> The "synthetic" office of the future may consist of rooms with variable sizes and forms, that constantly shrink or expand according to what activity is taking place inside. A room with many workers having a lively discussion could be increased in size, at the expense of unused or scarcely occupied rooms.

The future vision implied in these emerging works is one of a world where individuals have the capacity to freely transform or customize the surrounding built environment, new aesthetic styles flourish, city streets boast impeccable safety/accessibility for all, and citizens play increased roles in the planning and construction of their city landscapes. Contrary to past visions about future cities laid out in urban informatics [22, 46], what is plastic here is not only the transparent layers of digital information overlaid *atop* the city, but also the physical built environment made of glass, concrete and steel. What appears to be missing, however, are sober assessments of whether this vision has any chance of materializing (as UbiComp successfully has) in the real world, and if it does, what kinds of ramifications that will entail for society at large.

CRITICAL REFLECTION

We have shown how varied efforts are now emerging that aim at digitizing architectural space, but also how they are still in phases of early development, where optimism and fascination take center stage instead of critical assessments of their feasibility and implications. While Weiser's original vision was at least as (if not far more) technically optimistic and ambitious, the vision has been variously shepherded, fleshed out and reshaped over the past 23 years as ideals dovetailed with reality. The real-world manifestation of UbiComp now unfolding before our eyes may be *messier* [11] than what Weiser (and the early pioneers of the field) had anticipated, but what has been lost in theoretical purity has been replaced by practical efficacy to benefit our lives. Likewise, efforts at digitizing the built environment will also need to be tempered, and steered away from their present juvenile states. Ideally, this should happen *right now*, as opposed to later. As Lanier notes [40], in digital technology early design decisions (regardless of whether they had been made based on sound logic) tend to become fixed in place as *de facto standards*, that are too entrenched to replace later with better-designed alternatives.

As the digitization of the built environment can be interpreted as a logical extension to UbiComp, many of the criticisms and reflections on Weiser's vision made over the past two decades should be applicable here as well. Below, we will list some of the most notable commentaries on the UbiComp ideal raised within the academic community, and examine their relevance to the nascent attempts at realizing habitable bits.

The Illusion of Universality

Weiser's vision (or at least its representation in his essay) has been called out as being inherently paternalistic [19], built on an implicit assumption that his lab in Silicon Valley can serve as some modern equivalent of a colonialist capital, where the most important technical breakthroughs exclusively originate and from which they subsequently "trickle down" towards the rest of the world. Reality has proven this model to be wrong. Technical innovation is carried out by a multipolar network of individuals and groups that cannot be pinned down based on either geography (*Silicon Valley*) or institution type (*research laboratory*), and the same technology is often adopted in entirely separate ways by groups operating under different economic, cultural or social contexts [32]. The real-world manifestation of UbiComp is a global achievement, and its product is anything but a homogeneous, universal entity.

The same criticism wholly applies to the digitization of architectural space. Although in the scenario presented earlier, Sal now lives in a dense city center as opposed to suburbia (which is to some extent our deliberate decision to reflect the societal changes that have occurred during the past 23 years, but more importantly is an acknowledgment of the fact that an increasing number of HCI/CS research now targets urban settings), but to think that such an environment can serve as a universal prototype for the entire future world is just as naive as assuming that Xerox PARC could fit the bill two decades ago.

From Vision to Messy Reality

Weiser's Sal inhabited a world where the hundreds/thousands of computing devices spread across the environment all work together seamlessly and faultlessly. This has not yet been materialized, and we have no good reason to think it will ever be. Weiser had predicted that mobile devices (*tabs and pads*) will not be personal, but exist in large numbers scattered across the environment like post-it notes. Clearly this did not come true; one convincing explanation for this [5] is that Weiser failed to anticipate how passing around data between devices will continue to be so cumbersome and unreliable after so many years. Devices will not only have trouble communicating with each other, but will also often fail [15] due to numerous unpredictable reasons including software bugs, power outages, etc. Finally, humans (*users*) add another potential point of failure to the entire system [44], with our limited mental/physical capabilities and propensity to make mistakes. Far from the clockwork precision imagined by Weiser, the real-life UbiComp is a messy, imperfect system with limited built-in robustness.

The digitization of the built environment, if realized, will also take on a messy, imperfect form. The claim that in the future, transforming the architectural environment will be as easy as changing the wallpaper image on a present-day PC [57] takes for granted the smooth functioning of myriad, heterogeneous technical components that will be required in such a scenario, as well as glancing over the fact that switching the wallpaper image on a PC may not necessarily be an easy task for *everyone*. Also, if we were to turn into reality the idea (touched on in the scenario) of using digitized architecture for bottom-up/ DIY urban design, the most likely pitfall will not be technical, but will instead be what is perhaps the *messiest* aspect of human society—i.e., politics.

Social/Ethical/Political Implications

Weiser did not necessarily shy away from discussing the possible risks of his vision, as evidenced by his assertion that we investigate how to better deal with privacy. However, privacy is but one of a wide range of negative consequences argued to be brought about by UbiComp [8, 14]. Will UbiComp make our lives richer through automation, or will it make them even more stressful by blurring the line between work and leisure? When society increasingly relies on UbiComp infrastructure, what will be the costs (economic, social, etc.) of its malfunctions and failures? How much environmental damage will result from manufacturing all these new digital devices, that use rare materials and are largely non-recyclable? These are only a few of the many potential issues raised within the academic community, that have actually turned out to be grave concerns over the past two decades. Such concerns are not only carried over to the digitization of the built environment, but are often exacerbated, owing to the increased scale.

THE ROLES OF HCI RESEARCH

Despite being accused of numerous oversights and shortcomings, UbiComp as a concept has been remarkably successful, providing theoretical foundations for a wide range of technological wonders that we now take for granted. (So successful, that Abowd [5] has declared it to have all but "disappeared"—i.e., the concept is now so widely accepted that it is no longer possible to define any work as being *uniquely UbiComp*.) The HCI community has made a range of contributions instrumental to this process, exhibiting a distinct set of assets that make it well-equipped to take on similarly pivotal roles in the eventual realization of habitable bits. Below, we will list three different ways in which the community can contribute in further exploring this research trajectory, steering the efforts we have discussed so far toward more constructive directions.

As a Home for Vision-Oriented Discussions

One distinguishing attribute of the HCI community is its penchant for placing sweeping visions regarding the evolution of computing at the forefront of discussions, as opposed to being concerned narrowly with particular technical domains. While HCI may not be the community best suited for bringing about the most fundamental technical innovations either for responsive, augmented or printable architecture, its proven record in nurturing and promoting a concept makes it the most suitable community for rigorous discussions regarding the overall narrative to take place—e.g., whether the digitization of architectural space is a real, ongoing phenomenon or a mere illusion, whether it is a worthy extension to UbiComp or a trivial subfield, how can the vision be directed and fleshed out, what repercussions will arise for which domains, etc.

Though such discussions may rightfully take place outside of HCI, one would be hard-pressed to name another community with as respectable a tradition of accepting vision-oriented research (e.g., Ishii and Ullmer [29]) as first-rate academic contributions; within HCI, discourse on habitable bits can potentially take center stage, not relegated to the fringes.

As a Birthplace of New Design Methodologies/Toolkits

Perhaps unsurprisingly given its long favorable stance toward application-driven research, HCI has been the birthplace of a number of design methodologies [27, 39], prototyping techniques [6], toolkits [53], etc., that have subsequently been widely adopted in both research and practice. Many of these techniques are aimed at assisting designers effectively collect and utilize information about target users/contexts, allowing them to iteratively create applications tailored to the *messy* and *heterogeneous* realities that had not been accounted for with sufficient depth in Weiser's original vision.

As with UbiComp, applications will again be *the whole point* [62] of habitable bits, and hence the community's concern for methodologies/toolkits should be of benefit if it can be guided into contributing to this direction. Established HCI methdologies will likely fail in the face of architecture-scale system design—we do not know how to iteratively develop systems for which creating a series of full-scale prototypes is not feasible, and we also do not know if existing methodologies are applicable to the design of systems whose life spans are measured in decades not months or years. A new set of techniques/tools will need to be devised, taking cues from multiple disciplines including conventional HCI and architectural design.

As a Multidisciplinary Hub

HCI has always maintained an unabashedly multidisciplinary scope, which is reflected in the makeup of its community that now enlists members with backgrounds in computer science, engineering, industrial design, psychology and philosophy to name a few. While alternative communities exist that already are rigorously exploring the intersection between digital technology and architecture / urban design (e.g., civil engineering, smart city research, computer-aided design), their focus is not as all-inclusive, and none of them has quite as rich a tradition of interdisciplinary collaboration as HCI.

This fact makes HCI a highly promising community to tackle questions that escape disciplinary silos; for example, how can we reconcile the notion of augmented architecture (that practically enables people to live in their own *solipsistic* fantasies) with the notion of shared, public space? No existing community can adequately respond to such questions, but HCI seems to have the best chances of *evolving* into one that can.

CONCLUSION

In this paper, we have described how technologies are emerging that aim at an eventual *digitization of architectural space*. We have reviewed relevant prior work, and exposed the optimistic future vision implied within these technical efforts. We have then offered a critique of this vision, by drawing on past criticisms raised against the original UbiComp ideal. Finally, we have described several ways in which the HCI community can make use of its unique set of strengths, in shaping the future of this nascent direction of research.

HCI has long been obsessed with injecting digital technology into the physical environment, and recent innovations such as shapeshifting UIs and physical prototyping toolkits are giving us ever greater capacities to customize and transform our surrounding physical environments. Nonetheless, as we have argued in this paper, HCI has generally treated architectural design as being *off limits* of sorts. The emerging efforts we have described in this paper signal a bold departure from that long-standing indifference, an attitude we hope will be adopted by the broader HCI community. We believe that the time is ripe for HCI to evolve into a field that studies and designs the environment of the future *in its totality*, not only its niche subset we have been preoccupied for so long. GUIs, TUIs, etc. have been thoroughly studied; the new frontier for HCI now lies in the study and design of *HUIs—Habitable User Interfaces*.

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