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Physical Computing's Connected and Shape-Changing Future

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Technologies have a way of unexpectedly upending established social practices, often at a pace far outstripping the ability of a given society to absorb or process disruptions with awareness. From stirrups to gunpowder to magnets, history teaches that even seemingly mundane objects have the capacity to change everything.[1]

Physical computing has become an umbrella term whose practitioners draw theoretical and practical inspiration from research in a cluster of associated research domains, including tangible interactions, human-material interactions, shape-changing interfaces, organic user interfaces, interactive materiality, and material ecology. For many, a common goal is to bridge analog and physical worlds by infusing objects with compute and sense-making capabilities, in some cases enabling changes in a material's physical characteristics. The most intriguing implementations also strip away layers of abstraction and allow people to interact directly with objects with fewer intermediate interfaces, potentially reducing interaction friction, improving legibility, and fulfilling unmet human needs (see the sidebar for a list of potential applications).

The transformation of material objects into intelligent, information-rich ones holds great promise for fruitful partnerships between humans and technology. However, new opportunities also bring new challenges. It behooves us to examine how these new objects impact humans so that we can thoughtfully engineer systems that are mindful of our social practices—sidestepping potentially troubling outcomes and creating technologies worth having.

NOTEWORTHY TRANSITIONS

At this point in time, several transitions associated with physical computing stand out as being particular worthy of further scrutiny. I will elaborate on two.

How will we discover what knowledge is embedded in a particular object, as well as the limits of that knowledge?

From Material to Informational

The first concerns the shift from the *material* to the *informational* and presents questions about how interactions between humans, objects, and physical spaces will change over time. From shaping the way that we configure space to guiding the daily flows of activities, our built environments (and the objects within them) organize our lives.[2] However, in a world in which complex interactivities will be designed into even the most ordinary "stuff"—from faucets to furniture to walls themselves[3]—how will we go about determining an information object's utility, intended use, or capacity?[4] How will we discover what knowledge is embedded in a particular object, as well as the limits of that knowledge? More importantly, how can technological designs be adapted to anticipate and meet the needs of their human users, and not the other way around?

From Contextual to Universal

The second transition concerns an acceleration of merging social contexts brought about by novel data flows that connect and enliven these new informational objects. By selectively embedding objects with computing technologies, we enable new forms of data collection, analysis, and distribution, eroding natural data dams that have, up until now, shaped social conceptions of privacy. What might be the consequences of unexpected data tides, eddies, and floods? If the future is one in which our devices are watching us, listening to us, and even physically reconfiguring themselves to enhance our experiences, are we still able to truly do, feel, be, share, and withhold portions of ourselves at will?

SOCIAL IMPACT

PHYSICAL COMPUTING APPLICATION AREAS

What does the future hold? Virtual, in-air touchpad interfaces that enable real-time sensing of arm, hand, and finger positions could support surgical training by tracking fine hand movements.[1] Deformable interfaces that mimic mechanical properties of anatomical materials, water, and clay could help medical practitioners distinguish between tumor types, or assist geologists in modeling tsunami or earthquake outcomes.[2] Screens that curve inward, remain flat, or skitter away in response to the presence of authorized (or unauthorized) persons could provide better privacy, security, and personalization.[3] Water faucets that narrow their aperture or bend away from users could provide unobtrusive nudges to conserve in periods of higher-than-normal water usage.[3] Shape-changing tablets with co-located 3D graphics could simulate wave frequency and wind strength.[4] Tactile representations of navigable spaces (and more),[5] such as insoles that buzz to instruct a wearer to change direction, could improve accessibility and correct some setbacks unwittingly imposed upon communities for whom flat screens might be as functionally meaningless as sheets of glass.[6]

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INTERACTING WITH INFORMATIONAL OBJECTS

A central goal of design is to make objects and interfaces disappear—to get out of the way and let users achieve their goals. Designer Don Norman, for example, explicitly challenges developers to create tools that "fit the task so well that [they] become part of the task, feeling like a natural extension of the work, a natural extension of the person."[5]

Over the past decades, an influx of flat-screen technologies have shifted the daily human experience from one in which the vast majority of interaction affordances were readily apparent through objects' physical properties, such as cup handles that invite grasping and doorknobs that invite turning, to one in which the execution of even simple tasks requires explicit *signifiers*, or indicators of use.[5] Flexible and shape-changing interfaces appear to be introducing yet another phase of interactivity, in which direct, intuitive relations between objects and human users will reemerge as a priority, but without explicitly signaling the existence or management of the full set of interaction possibilities.

This presents an interesting challenge. As our environments become rich with "physical interfaces [that] can physically change to accommodate different users, uses, and contexts,"[6] are we moving toward a reality that has the appearance of being concrete and unchanging, but that is actually far less perceptible or discoverable?[7] When presented with new materialities, will we be more able to superficially engage with objects but less able to understand what they really do, what they really know, and who they really talk to? And if so, how should we, as developers, designers, and users, set about managing this complexity?

Although answers to these questions are far from settled, one early intriguing approach was taken by the MIT Media Lab's theoretical explorations of "radical atoms"—materials that can dynamically change their form and appearance to make information directly manipulable. In this line of research, objects change shape to reflect changes in their underlying computational states, such that affordances change concomitantly and dynamically in order to inform users of these alterations.[8] [See this issue's Interview department for a related discussion with Hiroshi Ishii.]

But dynamic affordances raise additional intriguing questions. As each generation has discovered, the introduction of new technologies transforms the things we think about, the things we think with, and the arenas in which we think.[1] How might early learners in future generations come to conceptualize object constancy, time, and even theory of mind when their daily interactions are dominated by objects with readily changeable areas, curvatures, and densities, and in which each form factor comes with an attendant set of computational capabilities customized to particular users,[9] perhaps appearing to merge with the ambient environment altogether?[10]

Intelligence and connectivity also reconfigure connections between objects, our environments, and ourselves, leading to an erosion of boundaries and an accompanying expansion of connected systems. Some predict that we will continue to become immersed in the so-called "infosphere" as technologies move from being mere enhancements of our bodies (like hammers) to augmenting interfaces between different environments (like washing machines) to re-engineered realities, in which large, distributed, and connected systems envelope us, altering how we use space and how we configure our bodies in relation to one another.[11]

Philosopher Luciano Floridi argues, for example, that conflating the material/physical with the informational reshapes our relationship with our physical environments and even our own informational identities, leading to new notions of *ourselves* as informational objects that collect experiences, keep memories, and transmit curated, reshaped historical narratives of our own lives. In Floridi's view, future generations will be doubly cursed: Forced to acquire unwanted characteristics and disallowed the possibility of forgetting or reinvention, they will nonetheless feel "deprived, excluded, handicapped, or poor to the point of paralysis and psychological trauma…like fish out of water"[11] if ever disconnected from the infosphere.

UNDERSTANDING ERODING BOUNDARIES

A second important consequence of fusing physical and computational environments is the new prospect of collecting, analyzing, and distributing vast amounts of personal data that support inferences about people's habits, preferences, lifestyles, and social affiliations. As the engineering accomplishments of physical computing advance, so does the importance of understanding how products, data flows, and policies can be architected to respect user privacy and maximize fairness. Although individuals might be eager to sample new technologies, appearing on the surface to forsake privacy for convenience or utility, research suggests that a host of doubts lurk beneath: "Why is this object here with me, and whose interests is it serving—mine, the company who made it, or the providers of the delivered services? What are the implications of these new information flows for me, my family, and society? Should I participate in this brave new world?"

Analytic philosopher scholar Helen Nissenbaum has argued that people do not care about having complete control over information about themselves. Rather, what they care about is that information is shared *appropriately*.[12] Nissenbaum's privacy framework of contextual integrity provides a process for determining the appropriateness of new information flows by reference to the ends and values embedded within a particular social context, such as home life, employment, or medical care. An indiscretion confessed to a trusted family member might be considered "too much information" for one's work colleagues; health data willingly shared with a medical professional bound by the Hippocratic Oath might be considered "off limits" to a commercial wellness app; location data given to a navigation service in exchange for route planning might take on a new meaning when it is later shared with law enforcement. As Nissenbaum explains, "when actions or practices violate entrenched informational norms, they provoke protest, indignation, or resistance. When actions or practices are in compliance, they respect contextual integrity."[12] From this perspective, determining whether and how new information flows violate privacy requires an assessment of whether and how they violate or enhance current contextual social norms.[13]

However, a central challenge to privacy today is that physical computing is hastening the blurring of previously well-established contextual boundaries. To take but one example, consider so-called "aging-in-place" devices and services. Embedding sensors in common household objects such as refrigerators, door locks, and even mattresses has the laudable aim of helping the elderly maintain independence and forestall moves to assisted living facilities. But recent analyses make clear that this implementation of physical computing has created a new ecosystem most accurately conceptualized as, among other things, a hybrid of home life and clinical medical care, each context of which has radically different norms of appropriate information sharing.[13] In one, information might facilitate a sense of camaraderie with family and friends. In another, it might present thorny issues regarding compliance, adherence, or physical safety, threatening the cost or availability of insurance. Similarly, smart home thermostats, lighting, and water-monitoring services are caught in a liminal space between norms of data sharing in the service of energy-saving, and norms that keep home life free from potentially meddlesome outside parties.[14]

This transition toward making private activities more easily seen, tracked, and potentially controlled by others matters for several reasons, not least because in technology, as with many domains, "the benefits and deficits are not distributed equally,"[1] and it is not always clear who will "win" and who will lose.[1] Clear and visible accountability, as well as signals of loyalty and discretion, will become particularly important as computation becomes further embedded in structural elements in our environments, including furniture, walls, and other infrastructural components that are able to observe, react, and always remember.

RECOMMENDATIONS

We are still in the earliest days of determining how new systems should behave when facing uncertain circumstances. In practice, which positive steps must be taken to maximize human value and prevent or minimize harm? There are no easy answers, but for now, I suggest that we think aspirationally. What would a "good" future world look like? How can physical computing systems be designed to bring that future closer?

To start, we would be wise to optimize for coordination, discoverability, and understanding.[3] *Coordinating* with humans means complementing, rather than duplicating, our strengths and creating objects that understand and work with human mental models, rather than imposing their own. *Discoverability* and *understanding* challenge us to create the conditions under which humans can easily grasp core system functionalities and comprehend its basic operations and limitations. This entails also thinking carefully about what types of feedback are informative and actionable without being too irritating or intrusive, too often.

From a privacy and information flow perspective, best practices suggest designing privacy features into systems at the outset, rather than attempting to tack them on at the end of the development process.[15] In practice, this means carefully exploring the aims, values, and ends of the social context in which a particular technology or set of technologies will be implemented and creating an integrated set of information flow settings that enhance these values. If contextual boundaries are blurry, the challenge becomes determining how to design for the optimum degree of transparency and granular control: when, how, and how frequently should users be offered information about what information is being collected about them, how it is being processed, stored, and distributed? What types of simple tools would allow them to selectively dismiss or reject unwanted information flows without losing access to core services?

In this vein, we might look beyond task objectives and toward larger social goals. Luciano Floridi introduces the term "infraethics," which he defines as "the design of environments that can facilitate ethical choices, actions, or processes."[11] Different from Ethics by Design, which privileges a set of behaviors pre-determined by a designer to meet particular ethical standards, a "pro-ethical" design privileges user reflection.

For example, rather than designing a system with defaults and allowing a person to opt in or opt out (which carries different social implications in the cases of say, information collection vs. organ donation vs donating grocery bag fees to charity), a pro-ethical system would leave choices open and ask a user to make a decision before he or she can proceed with a transaction. In this approach, the challenge is to first create the reflection infrastructure (infraethics) and then approach the contents (ethics) itself, considering how to present the implications of various alternative choices while being mindful of the nudges that design imposes upon human users.

FUTURE APPLICATIONS: BUILDING WITH SELF-AWARENESS

Looking ahead, much interesting work will be happening in a variety of production environments, where a shift from instruction-based to behavior-based fabrication offers intriguing possibilities for industry. Sometimes referred to as Industry 4.0 or the Fourth Industrial Revolution, a merger of material synthesis and connected computing is ushering in an ecosystem in which machines embedded with sensors and actuators are predicted to substitute real-time physical sensing for predictive modeling. No longer limited to executing predetermined tasks, robotic entities will be able to sense, learn, and create adaptively, reconfiguring themselves to new environments.[16]

In the architectural and design domain, scholars such as Achim Menges have asked, "what happens if the production machine no longer remains just the obedient executor of predetermined instructions, but begins to have the capacity to sense, react and act; in other words, to become self-aware?"[17] A large-scale adoption of machines that "self-predict, self-configure, and self-organize"[17] could have enormous economic upsides for manufacturers that benefit from dynamically reconfigured and streamlined workflows. Data from supply chains and production lines will enable factories to keep track of their own (and each other's) production and maintenance needs, adjust performance in real time to meet fluctuating targets, and even reconfigure themselves, taking into consideration the state of the system as a whole. Digitization of manufacturing technologies will enable greater individualization, bringing new opportunities in fields such as automotive design.[18]

This transition will also implicate system security, reliability, and, no less pressing, employment prospects for the humans whose professional expertise in operating complex machinery may be subjected to new demands made for, and perhaps by, replacements of the objects they once controlled. As machines begin to break free from deterministic instructions and train themselves, we would be wise to ensure that they receive human guidance along the way. Whether for purposes of planning, operations, or maintenance and repair, human input is critical for developing procedures for assigning control, accountability, and liability when systems fail.

Let us remember that even the most promising new technologies may reinforce social inequalities and create new forms of disadvantage for which we are ill-equipped to deal. Developing a stronger sense of what really matters to people—politically, economically, and culturally—will set us on a path toward creating new technologies that are not merely transformative but also responsive to human needs.[19]

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