Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms

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ABSTRACT
This paper presents our vision of Human Computer Interaction (HCI): "Tangible Bits." Tangible Bits allows users to "grasp & manipulate" bits in the center of users' attention by coupling the bits with everyday physical objects and architectural surfaces. Tangible Bits also enables users to be aware of background bits at the periphery of human perception using ambient display media such as light, sound, airflow, and water movement in an augmented space. The goal of Tangible Bits is to bridge the gaps between both cyberspace and the physical environment, as well as the foreground and background of human activities.

This paper describes three key concepts of Tangible Bits: interactive surfaces; the coupling of bits with graspable physical objects; and ambient media for background awareness. We illustrate these concepts with three prototype systems – the metaDESK, transBOARD and ambientROOM – to identify underlying research issues.

Keywords
tangible user interface, ambient media, graspable user interface, augmented reality, ubiquitous computing, center and periphery, foreground and background

INTRODUCTION: FROM THE MUSEUM
Long before the invention of personal computers, our ancestors developed a variety of specialized physical artifacts to measure the passage of time, to predict the movement of planets, to draw geometric shapes, and to compute [10]. We can find these beautiful artifacts made of oak and brass in museums such as the Collection of Historic Scientific Instruments at Harvard University (Fig. 1).

We were inspired by the aesthetics and rich affordances of these historical scientific instruments, most of which have disappeared from schools, laboratories, and design studios and have been replaced with the most general of appliances: personal computers. Through grasping and manipulating these instruments, users of the past must have developed rich languages and cultures which valued haptic interaction with real physical objects. Alas, much of this richness has been lost to the rapid flood of digital technologies.

We began our investigation of "looking to the future of HCI" at this museum by looking for what we have lost with the advent of personal computers. Our intention was to rejoin the richness of the physical world in HCI.

BITS & ATOMS
We live between two realms: our physical environment and cyberspace. Despite our dual citizenship, the absence of seamless couplings between these parallel existences leaves a great divide between the worlds of bits and atoms. At the present, we are torn between these parallel but disjoint spaces.

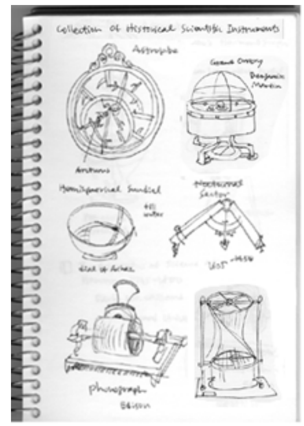

Figure 1 Sketches made at Collection of Historical Scientific Instruments at Harvard University

We are now almost constantly "wired" so that we can be here (physical space) and there (cyberspace) simultaneously [14]. Streams of bits leak out of cyberspace through a myriad of rectangular screens into the physical world as photon beams. However, the interactions between people and cyberspace are now largely confined to traditional GUI (Graphical User Interface)-based boxes sitting on desktops or laptops. The interactions with these GUIs are separated from the ordinary physical environment within which we live and interact.

Although we have developed various skills and work practices for processing information through haptic interactions with physical objects (e.g., scribbling messages on Post-It™ notes and spatially manipulating them on a wall) as well as peripheral senses (e.g., being aware of a change in weather through ambient light), most of these practices are neglected in current HCI design because of the lack of diversity of input/output media, and too much bias towards graphical output at the expense of input from the real world [3].

Outline of This Paper
To look towards the future of HCI, this paper will present our vision of Tangible Bits and introduce design projects including the metaDESK, transBOARD and ambientROOM systems to illustrate our key concepts. This paper is not intended to propose a solution to any one single problem. Rather, we will propose a new view of interface and raise a set of new research questions to go beyond GUI.

FROM DESKTOP TO PHYSICAL ENVIRONMENT
In 1981, the Xerox Star workstation set the stage for the first generation of GUI [16], establishing a "desktop metaphor" which simulates a desktop on a bit-mapped

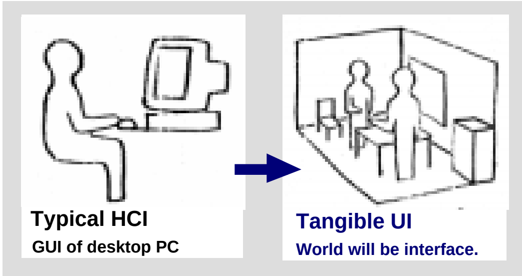

Figure 2 From GUI to Tangible User Interfaces

screen. The Star was the first commercial system which demonstrated the power of a mouse, windows, icons, property sheets, and modeless interactions. The Star also set several important HCI design principles, such as "seeing and pointing vs remembering and typing," and "what you see is what you get." The Apple Macintosh brought this new style of HCI into the public's attention in 1984, creating a new stream in the personal computer industry [1]. Now, the GUI is widespread, largely through the pervasiveness of Microsoft Windows.

In 1991, Mark Weiser (Xerox PARC) published an article on his vision of "Ubiquitous Computing" [18], illustrating a different paradigm of computing and HCI which pushes computers into the background and attempts to make them invisible.

The aim of our research is to show concrete ways to move beyond the current dominant model of GUI bound to computers with a flat rectangular display, windows, a mouse, and a keyboard. To make computing truly ubiquitous and invisible, we seek to establish a new type of HCI that we call "Tangible User Interfaces" (TUIs). TUIs will augment the real physical world by coupling digital information to everyday physical objects and environments. Fig. 2 illustrates the transition of HCI from the GUI of desktop PCs to Tangible User Interfaces which will change the world itself into an interface.

We see the locus of computation is now shifting from the desktop in two major directions: i) onto our skins/bodies, and ii) into the physical environments we inhabit. The transition to our bodies is represented by recent activities in the new field of "wearable computers" [13]. We are focusing on the second path: integration of computational augmentations into the physical environment. Our intention is to take advantage of natural physical affordances [15] to achieve a heightened legibility and seamlessness of interaction between people and information.

GOALS OF TANGIBLE BITS

"Tangible Bits" is an attempt to bridge the gap between cyberspace and the physical environment by making digital information (bits) tangible. We are developing ways to make bits accessible through the physical environment. Our key concepts are:

1) *Interactive Surfaces*: Transformation of each surface within architectural space (e.g., walls, desktops, ceilings, doors, windows) into an active interface between the physical and virtual worlds;

2) *Coupling of Bits and Atoms*: Seamless coupling of everyday graspable objects (e.g., cards, books, models) with the digital information that pertains to them; and

3) *Ambient Media*: Use of ambient media such as sound, light, airflow, and water movement for background interfaces with cyberspace at the periphery of human perception.

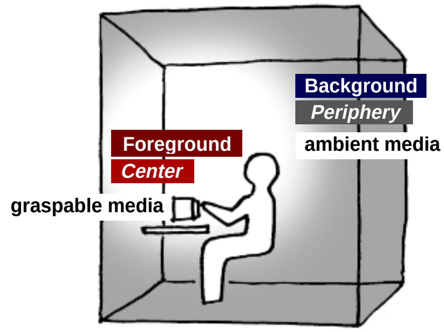

Figure 3 Center and Periphery of User's Attention within Physical Space

Ultimately, we are seeking ways to turn each state of physical matter – not only solid matter, but also liquids and gases – within everyday architectural spaces into "interfaces" between people and digital information. We are exploring ways of both improving the quality and broadening the bandwidth of interaction between people and digital information by:

- allowing users to "grasp & manipulate" foreground bits by coupling bits with physical objects, and
- enabling users to be aware of background bits at the periphery using ambient media in an augmented space.

Current HCI research is focusing primarily on foreground activity and neglecting the background [2]. However, subconsciously, people are constantly receiving various information from the "periphery" without attending to it explicitly. If anything unusual is noticed, it immediately comes to the center of their attention. The smooth transition of users' focus of attention between background and foreground using ambient media and graspable objects is a key challenge of Tangible Bits.

RELATED WORKS

Our work is inspired by the vision of "Ubiquitous Computing" [18] and the new stream of "Augmented Reality" research [20, 7, 9, 4]. The notion of "foreground/background" [2] also has stimulated our vision. Tangible Bits is also directly grounded on the previous works of ClearBoard [12] and Graspable User Interfaces [8]. Interactions with many media artists and product designers have also influenced the development of our vision.

Ubiquitous Computing

Mark Weiser (Xerox) proposed a vision of Ubiquitous Computing in which access to computational services is delivered through a number of different devices, the design and location of which would be tailored to support various tasks. In addition to this ubiquity, he stressed that the delivery of computation should be "transparent." His team at PARC implemented a variety of computational devices including Tabs, Pads, and Boards, along with the infrastructure which allows these devices to talk with each other.

Our work has been stimulated by Weiser's vision, but it is also marked by important differences. The Tab/Pad/Board vision is largely characterized by exporting a GUI-style interaction metaphor to large and small computer terminals situated in the physical environment.

While this approach clearly has a place, our interest lies in looking towards the bounty of richly-afforded physical devices of the last few millennia and inventing ways to re-apply these elements of "tangible media" augmented by digital technology. Thus, our vision is not about making "computers" ubiquitous per se, but rather about awakening richly-afforded physical objects, instruments, surfaces, and spaces to computational mediation, borrowing perhaps more from the physical forms of the pre-computer age than the present.

Augmented Reality

Augmented Reality (AR) (or Computer-Augmented Environments) is a new research stream which tries to answer the question of how to integrate the "real world" and computational media [20, 7, 9, 4]. DigitalDesk (Wellner) [20] is one pioneering work which demonstrated a way to merge physical and digital documents by using video projection of computer display onto a real desk with physical documents.

The most common AR approach is the visual overlay of digital information onto real-world imagery with see-through head-mounted (or hand-held) display devices or video projections. Our approach in Tangible Bits is differentiated by a strong focus on graspable physical objects as input rather than by considering purely visual augmentations, and in the combination of ambient media with graspable objects.

ClearBoard

ClearBoard [12] (Ishii & Kobayashi) was designed to achieve a seamless integration of shared drawing space and interpersonal space for geographically distributed shared drawing activity. ClearBoard triggered the idea of changing a "wall" from a passive architectural partition to a dynamic collaboration medium that integrates distributed real and virtual spaces. ClearBoard led us to a vision of new architectural spaces where all the surfaces including walls, ceilings, windows, doors and desktops become active surfaces through which people can interact with other spaces, both real and virtual.

Passive Real-World Interface Props

Hinckley et al. has developed passive real-world interface props for 3D neurosurgical visualization [11]. Here, users are given physical props (e.g. head viewing prop, cutting-plane selection prop) as a mechanism for manipulating 3D models within a traditional computer screen. They worked towards an interface which facilitates natural two-handed interaction and provides tactile and kinesthetic feedback. Our work differs from the passive props approach in its seamless integration of input and output for supporting physical interactions.

Figure 4 ClearBoard [12]

Figure 5 Bricks [8]

Figure 6 Marble Answering Machine (Courtesy D. Bishop)

Bricks: Graspable User Interfaces

Graspable User Interfaces [8] (Fitzmaurice, Ishii & Buxton) allow direct control of virtual objects through physical handles called "bricks." Bricks can be "attached" to virtual objects, thus making virtual objects physically *graspable*. Although a mouse provides time-multiplexed input (one device to control different functions at different points in time), Bricks offer a concurrence between space-multiplexed input and output. Bricks can be attached to virtual objects to serve as dedicated transducers, each occupying its own space. Bricks encourage two-handed direct manipulation and allow parallel input specification, thereby improving the communication bandwidth with the computer. This work lead us to a strong focus on graspable physical objects as a means to access and manipulate bits within the Tangible Bits project.

Marble Answering Machine

Durrell Bishop, while a student at the Royal College of Art (RCA), designed a prototype telephone answering machine to explore ways in which computing can be taken off the desk and integrated into everyday objects. In the marble answering machine, incoming voice messages are physically instantiated as marbles (Fig. 6). The user can *grasp* the message (marble) and drop it into an indentation in the machine to play the message. The user can also place the marble onto an augmented telephone, thus dialing the caller automatically [5]. The original concept animation was followed by several physical prototypes which realized the answering machine along with a family of other physical instantiation of applications.

This physical embodiment of incoming phone messages as marbles demonstrated the great potential of making digital information graspable by coupling bits and atoms.

Live Wire

Natalie Jeremijenko designed a beautiful instrument called Live Wire while an artist in residence at Xerox PARC [19]. It is a piece of plastic cord that hangs from a small electric motor mounted on the ceiling. The motor is electrically connected to the area Ethernet network, such that each passing packet of information causes a tiny twitch of the motor. Bits flowing through the wires of a computer network become tangible through motion, sound, and even touch. The activity of the wire is visible and audible from many offices without being obtrusive, taking advantage of peripheral cues. This work encouraged us to think about ambient media as a general mechanism for displaying activities in cyberspace.

Fields and Thresholds: Benches

Anthony Dunne and Fiona Raby at the RCA presented "Fields and Thresholds" [6] at the Doors of Perception 2 conference. In this work, they explored ways to blur the boundary between "telematic" spaces and physical spaces and to create a sense of another place using non-visual media such as acoustic and thermal transducers. As an example, they described two cold steel benches located in different cities. When a person sits on one of these benches, a corresponding position on the other bench warms, and a bi-directional sound channel is opened. At the other location, after feeling the bench for "body heat," another person can decide to make contact by sitting near the warmth. Initially the sound channel is distorted, but as the second party lingers, the audio channel clears. This subtle and poetic representation of the presence of others stimulated the conceptual design of our ambientROOM.

TANGIBLE BITS: RESEARCH PROTOTYPES

"Tangible User Interfaces" emphasize both visually-intensive, "hands-on" foreground interactions, and background perception of ambient light, sound, airflow, and water flow at the periphery of our senses. The metaDESK and transBOARD are prototype systems for exploring the use of physical objects as a means to manipulate bits in the center of users' attention (foreground). On the other hand, the ambientROOM is focused on the periphery of human perception (background).

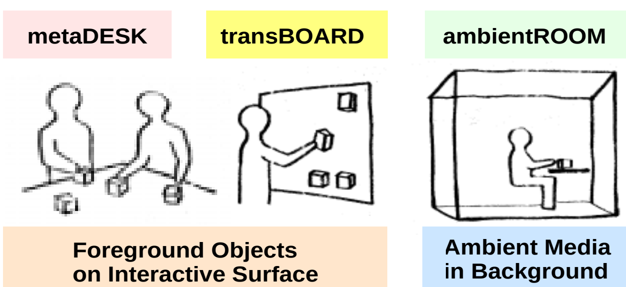

Fig. 7 Three Research Platforms of Tangible Bits

metaDESK

In the metaDESK design, we have tried to push back from GUIs into the real world, physically embodying many of the metaphorical devices (windows, icons, handles) they have popularized. Simultaneously, we have attempted to push forward from the unaugmented physical world, inheriting from the richness of various historical instruments and devices often made "obsolete" by the advent of personal computers. This design approach of metaDESK is illustrated in Fig. 8. Fig. 9 illustrates examples of the physical instantiation of GUI elements such as windows, icons, and handles in Tangible User Interfaces. For example, the "activeLENS," an arm-mounted flat-panel display, is a physically instantiated *window* which allows haptic interaction with 3D digital information bound to physical objects.

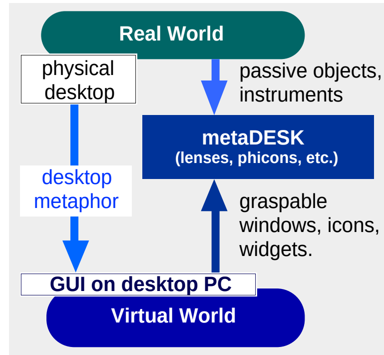

Figure 8 metaDESK design approach

The metaDESK consists of a nearly horizontal back-projected graphical surface; the "activeLENS," an arm-mounted LCD screen; the "passiveLENS," a passive optically transparent "lens" actively mediated by the desk; "phicons," physical icons; and instruments which are used on the surface of the desk. These physical objects and instruments are sensed by an array of optical, mechanical, and electro-magnetic field sensors embedded within the metaDESK, which is based on Input Technologies' VisionMaker™. The metaDESK "brings to life" these physical objects and instruments as elements of tangible interfaces.

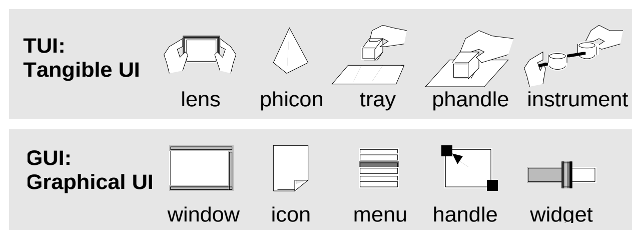

Figure 9 Physical instantiation of GUI elements in TUI

Tangible Geospace

Tangible Geospace is a prototype application of the metaDESK platform. Tangible Geospace uses physical models of landmarks such as MIT's Great Dome and Media Lab buildings as phicons to allow the user to manipulate 2D and 3D graphical maps of the MIT campus (Fig. 10, 11). By grasping a small physical model of the Great Dome and placing it onto the desk's surface, a two-dimensional map of MIT campus appears on the desk surface beneath the object, with the location of the Dome

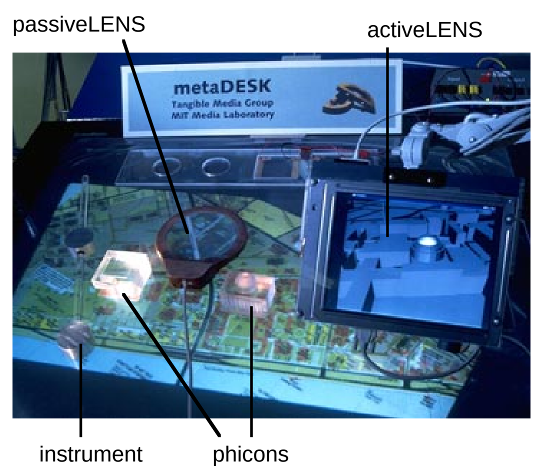

Figure 10 Tangible Geospace on metaDESK

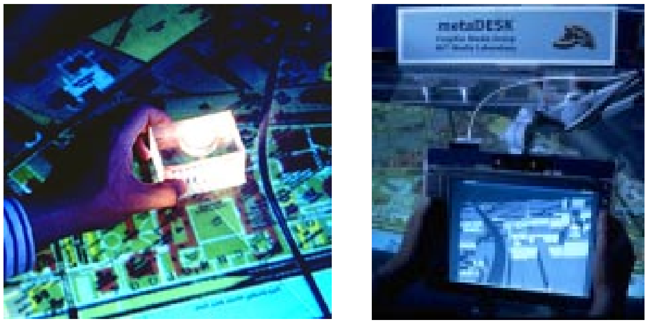

Figure 11 Phicon and activeLENS

Figure 12 Scaling and Rotation Device with embedded mechanical constraints

on the map bound to the physical location of the Dome phicon. (Fig. 11).

Simultaneously, the arm-mounted activeLENS displays a spatially-contiguous 3D view of MIT campus (Fig. 11). By grasping and moving the activeLENS (a physically embodied *window*), the user can navigate the 3D representation of campus building-space.

The Great Dome phicon acts both as a container of bits which represent the MIT campus, and as a handle for manipulating the map. By rotating or translating the Dome object across the desk surface, both the 2D desk-view and 3D activeLENS-view are correspondingly transformed. The user is thus interacting visually and haptically with three spaces at once—the physical-space of the Dome object; the 2D graphical space of the desk surface; and the 3D graphical space of the activeLENS.

The user may then take a second phicon, this time of the Media Lab building, and place it onto the surface of the desk. The map then rotates and scales such that the second phicon is bound to the location of the Media Lab building on the map. Now there are two physical constraints and handles on the MIT campus space, allowing the user to simultaneously scale, rotate, and translate the map by moving one or both objects with respect to each other.

Because each phicon serves as an independent locus of control, the user may grasp and manipulate both objects simultaneously with his/her two hands. Alternatively, two users may independently grasp separate building objects, cooperatively manipulating the transformation of the Geospace. In this fashion, there is no one locus of control as is true in point-and-click mouse interaction; rather, the interaction is constrained by the physics of the physical environment, supporting multiple pathways of single- and multi-user interaction.

By bringing a passiveLENS device onto the desk, the user may interact with satellite-imagery or future/past-time overlay views of the map space, or explore alternate interactions consistent with physical instantiation of the Magic Lens metaphor [17].

With two phicon objects on the desk, there is an issue of ambiguity that must be resolved. For instance, when one or both phicons are rotated independently, how should the application respond? We currently ignore this conflicting information, but could also imagine other interpretations such as warping the map view. To resolve this ambiguity, we designed a rotation-constraint instrument made of two cylinders mechanically coupled by a sliding bar as shown in Fig. 12. This instrument has mechanical constraints which prohibit independent rotation and realize distinct axes of scaling and rotation. By building in these physical constraints, we resolve the question of ambiguity in this particular case.

ambientROOM

The ambientROOM complements the graphically-intensive, cognitively-foreground interactions of the metaDESK by using ambient media – ambient light, shadow, sound, airflow, water flow – as a means for communicating information at the periphery of human perception. The ambientROOM is based on Steelcase's Personal Harbor™ unit, a 6' x 8' freestanding room, which we have augmented with MIDI-controllable facilities. The ambientROOM is designed to employ both the foreground and background of users' attention.

Figure 13 ambientROOM based on Personal Harbor™

In normal day to day interactions, we get information in two main ways. First, we get information from what we are focusing on, where our center of attention is directed. When we are speaking with a colleague in the office, we are consciously focusing on that person and receiving information directly from them. But at the same time, we are also getting information from ambient sources. We may have a sense of the weather outside from ambient cues such as light, temperature, sound, and air flow from nearby windows. We may also have an idea of the activities of colleagues in the area from the ambient sound and the visible presence of passers-by.

In contrast to the conscious foreground processing occurring in discussions with a colleague, much of this ambient information is processed through background communication channels. Our goal for the ambientROOM is to explore how we can take advantage of this natural

Figure 14 Phicons in ambientROOM

Figure 15 An ambient display : light reflection from water onto ceiling

parallel background processing using ambient media to convey information.

One focus of the ambientROOM is the use of ambient media to subtly display and communicate information which is not the user's primary foreground task. We are also concerned with providing handles for the seamless transition of the user's interaction between background and foreground information. In the real world, when a process that was not a focus of attention catches our interest, we are often able to seamlessly integrate it into our activity. Realizing HCI analogs of this fuzzy, fluid boundary between background and foreground is a challenging research opportunity.

To identify design issues within the ambientROOM, we have prototyped a simple scenario which suggests possible directions for continuing work. Within the ambientROOM, we have utilized phicons as handles and containers for "sources" and "sinks" of information. Imagine one's business is manufacturing toys, and the latest toy car product has just been advertised on the company Web site. In this example, we can imagine using the physical object of the toy car as a phicon representing a *source* of information, say, web-hits on the car-announcement Web page.

By grasping this car phicon and moving it into the proximity of some information *sink*, we can establish an ambient display of car web-page activity. For instance, by moving the phicon near a speaker in the ambientROOM, we can imagine activating a subtle audio display of associated web activity, where each web-hit to the car page is presented as the sound of raindrops. The sound of heavy rain would indicate many visits to the web page and success in attracting customer attention, while no rain might indicate poor marketing or a potential breakdown of the web server.

A steady pattering of rain might remain at the periphery of the user's attention, allowing the user to concentrate on foreground activities such as reading e-mail. However, if the sound of rain suddenly stops or grows louder, it will attract his attention, causing him to grasp the object and bring it onto the metaDESK, for example, displaying more detailed interactive graphical information about recent web page activity.

We prototyped the above interaction in the ambientROOM with passive physical phicons, simple MIDI-based infrared proximity sensors, and recorded sounds of rainfall linked to sample web activity levels. While we found this ambient display compelling, we also determined that at times the sounds of rain could be distracting. As an alternate display technology, we built a thin water tank outfitted with a solenoid-driven float which can be "pulled by bits." With each pull, the float creates a ripple on the surface of water. Light projected onto the water tank from above casts a subtle but poetic image of ripples on the ceiling of the room (Fig. 15). This new ambient display of bits in the room has been received enthusiastically by both artists and commercial sponsors who have visited our lab.

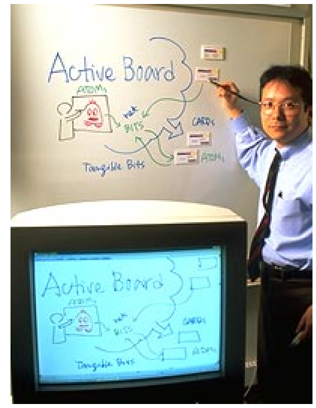

Figure 16 transBOARD: a networked digital whiteboard with hyperCARDs

Although ambient media is most often processed continually in the background, it can naturally move into the center of attention. The brain will naturally move the ambient information into the foreground either if it becomes anomalous or if there is a lull in the foreground concern. By using ambient media as an additional method to convey information, we are taking advantage of our brain's natural abilities as both a parallel processor and as an attention manager.

We have begun a new research project, "Ghostly Presence," to support awareness at the periphery by displaying the presence of remote people and their activities using ambient media and graspable physical representations.

transBOARD

The transBOARD is a networked digitally-enhanced physical whiteboard designed to explore the concept of interactive surfaces which absorb information from the physical world, transforming this data into bits and distributing it into cyberspace (Fig. 16).

The transBOARD supports Java-based distributed access to physical whiteboard activity. The stroke server and Java applet (developed by Chris Fuchs in our group) allow distributed users to graphically view both realtime and recorded drawing processes over the Internet, or potentially to express drawing activity through ambient display media within the ambientROOM (for instance, with a subtle sound of scratching produced from a wall surface).

The transBOARD was implemented on a SoftBoard™ product from Microfield Graphics, which monitors the activity of tagged physical pens and erasers with a scanning infrared laser. From the user's point of view, the transBOARD is nearly the same as an ordinary whiteboard, and minimally alters the familiar work practice of using a whiteboard.

The transBOARD supports the use of "hyperCARDs" (barcode-tagged paper cards) as containers of digital strokes. These magnetically-backed cards, which can be attached to the vertical surface of the transBOARD, are another example of phicons. In our demonstration scenario, when a card is attached to the surface during drawing sessions, monitored pen-strokes from the whiteboard are virtually "stored" within the card; in fact, they are being recorded on a web server to which the hyperCARD's barcode serves as a URL. In addition, the strokes are broadcast live to remote users who might be monitoring the session with an identical hyperCARD. The user can then keep the meeting contents within this card, perhaps bringing it to his office or home. If he puts this card on a conventional computer screen, it will automatically bring up the digital strokes stored in the source web server, without requiring manual entry of a filename or URL.

For the implementation of this prototype, we used a barcode wand to let the transBOARD or remote computer identify the card at the beginning of each session. However, we found scanning of the barcode with the wand to be quite cumbersome, and we are now designing a new version that uses wireless passive RF ID tag technology.

The surface of the transBOARD serves as a one-way filter for absorbing bits from the physical world into cyberspace. In contrast, the metaDESK surface is a bi-directional interactive surface spanning physical and virtual spaces. The lack of capability for displaying bits on the transBOARD makes an interesting contrast with the metaDESK which can both absorb and express digital information on its surface. We are planning to install a transBOARD-based activeLENS to augment the transBOARD's limited display capabilities.

DISCUSSIONS: OPTICAL METAPHORS

Through the design process of Tangible User Interfaces, we encountered many design problems which helped us to identify the most salient research issues. Among the many issues that we explored, we realized that metaphors which bridge physical and digital worlds are particularly interesting. In this section, we would like to discuss one user interface metaphor that can be applied seamlessly across the metaDESK, ambientROOM, and transBOARD platforms.

We found the metaphor of light, shadow, and optics in general to be particularly compelling for interfaces spanning virtual and physical space. We first implicitly invoked this metaphor by creating the activeLENS, an arm-mounted flat-panel display, modeled in both form and function upon the optical jeweler's magnifying lens. Exploring this same optical process, we created the passiveLENS, a transparent plexiglass surface brought to life by the back-projected metaDESK display.

Pushing further still, we applied the optical metaphor to the metaDESK's physical icons (phicons), and created the notion of "digital shadows." In physical space, illuminated objects cast shadows reflecting their physical substance. In augmented space, we reasoned, physical objects might also cast digital shadows which project information pertinent to their virtual contents. We have used this digital shadow concept in several of our prototypes.

Reflecting on the notion of digital shadows in Tangible Geospace, we were struck by considerations of where sources of digital, semantic, or virtual light might originate. So inspired, we have begun implementing an instrumented physical flashlight which projects various "wavelengths" of "virtual" or "semantic light" into the Tangible Geospace scene. In Tangible Geospace, this virtual light might cast digital shadows of various physical and virtual objects. For instance, the 3D building geometries of the MIT campus could be imagined not only to render "optically-constrained" shadows of buildings' physical forms, but also to generate shadows as a function of non-physical parameters of the geographical landscape, say, as a function of the research publications or sponsorship inflows of various buildings. Furthermore, we can think of projecting other "optical" qualities into the scene such that the rendering style changes from photorealistic to impressionistic.

The optical metaphor is not limited to the graphically-intensive surface of the metaDESK, but has also played a major role in our design of the ambientROOM. We have discussed at some length the use of ambient light, shadow, and reflection/refraction from moving water within the ambientROOM. Here, notions of light and shadow are used both literally as a medium for ambient display, and metaphorically for the play of light and shadow at the periphery of human perception. On the transBOARD, the optical metaphor is somewhat weaker due to the limited computer display facilities. However, we have considered mounting an "optical" activeLENS device onto the transBOARD, allowing users to spatially and temporally navigate local and remote drawings along with supporting digital media.

Perhaps the most compelling aspect of the optical metaphor is its seamless consistency with the physics of real space. By not only invoking but also obeying the optical constraints metaphorically imposed on our physical interface prototypes, we are able to maximize the *legibility of interface* of our creations. People know what to expect of a flashlight, know what to expect of lenses. By satisfying these expectations, we can realize truly seamless, "invisible" integration of our technologies with the physical environment.

Finally, the optical metaphor is a great source of inspiration for future work. Ideas about the interaction of digital light with physical space opens many new possibilities for literal and metaphorical uses of mirrors, prisms, virtual and physical transparency and opacity, and light of different spectrums and powers of penetration in the context of both foreground and backchannel information display.

CONCLUSIONS

This paper presented our vision of Tangible Bits which bridges the gap between the worlds of bits and atoms through graspable objects and ambient media in physical environments. Current GUI-based HCI displays all information as "painted bits" on rectangular screens in the foreground, thus restricting itself to very limited communication channels. GUIs fall short of embracing the richness of human senses and skills people have developed through a lifetime of interaction with the physical world.

Our attempt is to change "painted bits" into "tangible bits" by taking advantage of multiple senses and the multi-modality of human interactions with the real world. We believe the use of graspable objects and ambient media will lead us to a much richer multi-sensory experience of digital information.

Ishii met a highly successful PDA (Personal Digital Assistant) called the "abacus" when he was 2 years old. This simple abacus-PDA was not merely a computational device, but also a musical instrument, imaginary toy train, and a back scratcher. He was captivated by the sound and tactile interaction with this simple artifact. When his mother kept household accounts, he was aware of her activities by the sound of her abacus, knowing he could not ask for her to play with him while her abacus made its music. We strongly believe this abacus is suggesting to us a direction for the next generation of HCI.

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REFERENCES

1. Apple. Human Interface Guidelines: The Apple Desktop Interface. Addison-Wesley, 1987
2. Buxton, W. Integrating the Periphery and Context: A New Model of Telematics, in *Proceedings of Graphics Interface '95*, 239-246.
3. Buxton, W. (in press). Living in Augmented Reality: Ubiquitous Media and Reactive Environments. To appear in Finn, Sellen & Wilber (Eds.). *Video Mediated Communication.* Hillsdale, N.J.: Erlbaum.
4. Cooperstock, J.R., Tanikoshi, K., Beirne, G., Narine, T., Buxton, W. Evolution of a Reactive Environment, *Proceedings of CHI'95*, 170-177.
5. Crampton Smith, G. The Hand That Rocks the Cradle. I.D., May/June 1995, pp. 60-65.
6. Dunne, A. and Raby F. Fields and Thresholds. Presentation at the Doors of Perception 2, November 1994, http://www.mediamatic.nl/Doors/Doors2/-DunRab/DunRab-Doors2-E.html
7. Feiner, S., MacIntyre, B., and Seligmann, D. Knowledge-based augmented reality. *Commun. of the ACM*, 36(7), July 1993, 52-62.
8. Fitzmaurice, G.W., Ishii, H. & Buxton, W. Bricks: Laying the Foundations for Graspable User Interfaces, in *Proceedings of CHI'95*, 442-449.
9. Fitzmaurice, G., Situated Information Spaces and Spatially Aware Palmtop Computers. *Commun. ACM*, July 1993, Vol. 36, No. 7, 38-49.
10. Hambly, M., *Drawing Instruments 1580-1980*, Sotheby's Publications, London, 1988.
11 Hinckley, K., Pausch, R., Goble, J., and Kassel, N., Passive Real-World Interface Props for Neurosurgical Visualization, in *Proceedings of CHI '94*, April 1994, 452-458.
12. Ishii, H., Kobayashi, M. and Arita, K. Iterative Design of Seamless Collaboration Media, *Commun. ACM*, Vol. 37, No. 8, August 1994, 83-97.
13. Mann, S. 'Smart Clothing': Wearable Multimedia Computing and 'Personal Imaging' to Restore the Technological Balance between People and Their Environments, in *Proc. of ACM MULTIMEDIA* '96, November 1996, 163-174.
14. Negroponte, N. *Being Digital.* Alfred A. Knopf, Inc., New York, 1995
15. Norman, D. A. *Psychology of Everyday Things.* Basic Books, 1988
16. Smith, D. Designing the Star User Interface. *Byte*, April 1982, pp. 242-282.
17. Stone, M., Fishkin, K., and Bier, E. The Movable Filter as a User Interface Tool, in *Proceedings of CHI '94*, ACM Press, 306-312.
18. Weiser, M. The Computer for the 21st Century. Scientific American, 1991, 265 (3), pp. 94-104.
19. Weiser, M. and Brown, J.S., Designing Calm Technology. http://www.ubiq.com/hypertext/weiser/-calmtech/calmtech.htm, December 1995.
20. Wellner, P., Mackay, W., and Gold, R. Computer Augmented Environments: Back to the Real World. *Commun. ACM*, Vol. 36, No. 7, July 1993