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Emerging Frameworks for Tangible User Interfaces

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ABSTRACT

For more than thirty years, people have relied primarily on screen-based text and graphics to interact with computers. Whether the screen is placed on a desk, held in one's hand, worn on one's head, or embedded in the physical environment, the screen has cultivated a predominantly visual paradigm of human-computer interaction. In this chapter, we discuss a growing space of interfaces in which physical objects play a central role as both physical representations and controls for digital information. We present an interaction model and key characteristics for such "tangible user interfaces," and explore these characteristics in a number of interface examples. This discussion supports a newly integrated view of both recent and previous work, and points the way towards new kinds of computationally-mediated interfaces that more seamlessly weave together the physical and digital worlds.

INTRODUCTION

The last decade has seen a wave of new research into ways to link the physical and digital worlds. This work has led to the identification of several major research themes, including augmented reality, mixed reality, ubiquitous computing, and wearable computing. At the same time, a number of interfaces have begun to explore the relationship between physical representation and digital information, highlighting kinds of interaction that are not readily described by these existing frameworks.

Fitzmaurice, Buxton, and Ishii took an important step towards describing a new conceptual framework with their discussion of "graspable user interfaces" [Fitzmaurice 95]. Building upon this foundation, we extended these ideas and proposed the term "tangible user interfaces" in [Ishii 97]. Among other historical inspirations, we suggested the abacus as a compelling prototypical example. In particular, it is key to note that when viewed from the perspective of human-computer interaction (HCI), the abacus *is not an input device.* The abacus makes no distinction between "input" and "output." Instead, the abacus beads, rods, and frame serve as manipulable *physical representations* of numerical values and operations. Simultaneously, these component artifacts also serve as *physical controls* for directly manipulating their underlying associations.

This seamless integration of *representation* and *control* differs markedly from the mainstream graphical user interface (GUI) approaches of modern HCI. Graphical interfaces make a fundamental distinction between "input devices," such as the keyboard and mouse, as *controls;* and graphical "output devices" like monitors and head-mounted displays, for the synthesis of visual *representations*. Tangible interfaces, in the tradition of the abacus, explore the conceptual space opened by the elimination of this distinction.

In this chapter (based on [Ullmer 00]), we take steps towards a conceptual framework for tangible user interfaces. We present an interaction model and key characteristics for tangible interfaces (or "TUIs"), and illustrate these with a number of interface examples. We discuss the coupling between physical objects and digital information, taken both as individual and interdependent physical/digital elements. In the process, our goal is to identify a distinct and cohesive stream of research including both recent and decades-old examples, and to provide conceptual tools for characterizing and relating these systems under the common umbrella of "tangible user interfaces."

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A FIRST EXAMPLE: URP

To provide context for our discussions, we will begin by introducing an example interface: "Urp." Urp is a tangible interface for **ur**ban **p**lanning, built around a workbench that allows the direct manipulation of physical building models to configure and control an underlying urban simulation [Underkoffler 99a,b]. The interface combines a series of physical building models and interactive tools with an integrated projector/camera/computer node called the "I/O Bulb."

Under the mediation of the I/O Bulb, Urp's building models cast graphical shadows onto the workbench surface, corresponding to solar shadows at a particular time of day. The position of the sun can be controlled by turning the physical hands of a clock tool. The building models can be moved and rotated, their corresponding shadows transforming accordingly, to visualize intershadowing problems (shadows cast on adjacent buildings).

A "material wand" can be used to bind alternate material properties to individual buildings. For instance, when bound with a "glass" material property, buildings cast not only solar shadows, but also solar reflections. These reflections exhibit more complex (and less intuitive) behavior than shadows. Moreover, these reflections pose glare problems for urban drivers (roadways are also physically instantiated and graphically augmented by Urp.)

Finally, the "wind tool" is bound to a computational fluid flow simulation. By adding this object to the workbench, an airflow simulation is activated, with field lines graphically flowing around the buildings. Changing the wind tool's physical orientation correspondingly alters the orientation of the computationally simulated wind. A "wind probe" object allows point monitoring of the wind simulation's numerical results.

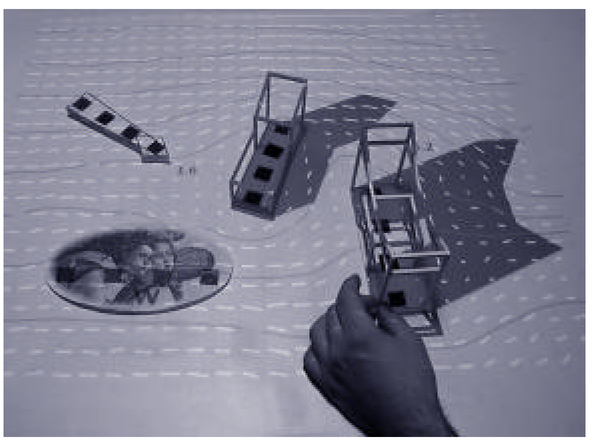


Figure 1: "Urp" urban planning simulation, with buildings, wind tool, and wind probe *(courtesy John Underkoffler)*

TANGIBLE USER INTERFACES

As illustrated by the above example, tangible interfaces give physical form to digital information, employing physical artifacts both as *representations* and *controls* for computational media. TUIs couple physical representations (e.g., spatially manipulable physical objects) with digital representations (e.g., graphics and audio), yielding interactive systems that are computationally mediated, but generally not identifiable as "computers" per se.

Clearly, traditional user interface devices such as keyboards, mice, and screens are also physical in form. Here, the role of physical representation provides an important distinction. For example, in the "Urp" tangible interface, physical models of buildings are used as physical representations of actual buildings. The physical forms of Urp's models (representing specific buildings), as well as their position and orientation upon the system's workbench, serve central roles in representing and controlling the state of the user interface.

In contrast, the physical form and position of the mouse hold little "representational" significance. Graphical user interfaces (GUIs) represent information almost entirely in transient visual form. While the mouse mediates control over the GUI's graphical cursor, its function can be equally served by a trackball, joystick, digitizer pen, or other "input peripherals." This invariance differs sharply from the Urp example, where the interface is closely coupled to the identity and physical configuration of specific, physically representational artifacts.

INTERACTION MODEL

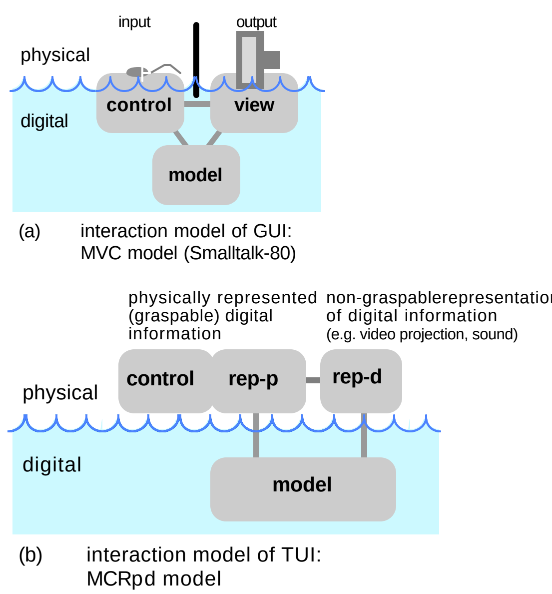
As we have discussed, tangible interfaces are centrally concerned with notions about representation and control. "Representation" is a rather broad term, taking on different meanings within different communities. In artificial intelligence and other areas of computer science, the term often relates to the programs and data structures serving as the computer's *internal* representation (or model) of information. In this chapter, our meaning of "representation" centers upon *external* representations – the external manifestations of information in fashions directly perceivable by the human senses.

We divide the space of external representations into two broad classes. First, we consider *physical representations* to be information that is physically embodied in concrete, "tangible" form.[2] Alternately, we consider *digital representations* to be computationally mediated displays that are perceptually observed in the world, but are not physically embodied, and thus "intangible" in form. For instance, we consider the pixels on a screen or audio from a speaker to be examples of digital representations, while we view physical chess pieces and chess boards as examples of physical representations.

Our concept of digital representations in some respects approximates audio/visual representations, or perhaps "intangible" representations. Clearly, even the "digital representations" of a CRT or speaker require physical phenomena to be perceptible to humans. By choosing the digital representations term, we seek to identify the transient displays that are products of ongoing computations. As a clarifying heuristic, when the power to a tangible interface is removed, it is the "digital representations" which disappear, and the embodied, persistent "physical representations" which remain. Tangible interfaces are products of a careful balance between these two forms of representation.

Traditional computer interfaces frame human interaction in terms of "input" and "output." Computer output is delivered in the form of "digital representations" (esp., screen-based graphics and text), while computer input is obtained from control "peripherals" such as the keyboard and mouse. The relationship between these components is illustrated by the "model-view-controller" or "MVC" archetype -- an interaction model for GUIs developed in conjunction with the Smalltalk-80 programming language. We illustrate the MVC model in Figure 2a. MVC highlights the GUI's strong separation between the digital representation (or *view*) provided by the graphical display, and the *control* capacity mediated by the GUI's mouse and keyboard.

Drawing from the MVC approach, we have developed an interaction model for tangible interfaces that we call "MCRpd," for "model-control-representation (physical and digital)". This model is illustrated in Figure 2b. We carry over the "model" and "control" elements from MVC, while dividing the "view" element into two subcomponents: *physical representations* ("rep-p") ar



Figures 2a,b: GUI and TUI interaction models

Where the MVC model of Figure 1a illustrates the GUI's separation between graphical representation and control, MCRpd highlights the TUI's integration of physical representation and control. This integration is present not only at a conceptual level, but also in physical point of fact – TUI artifacts *physically embody* both the control pathway, as well as a central representational (information-bearing) aspect of the interface.

[2] It is worth noting that the "tangible" term derives from the Latin words "tangibilis" and "tangere," meaning "to touch."

In this chapter, we will concentrate upon the space of interfaces where each element of the MCRpd model is clearly present, with an emphasis on the role of physical representation. However, it is important to note that a series of interesting interaction regimes are highlighted by relaxing these expectations. For instance, if we relax our *control* expectations, the space of "ambient media" is highlighted, where devices such as spinning pinwheels and rippling water are used as information displays [Ishii 97, Wisneski 98]. Alternately, if we relax our expectations of physical state (discussed more in the following section), interfaces such as the synchronized rollers of inTouch [Brave 98] or the graspable handles of Bricks [Fitzmaurice 95] are brought to the fore. While we do not intend to exclude these kinds of systems from the larger tangible interface design space, we will focus on interfaces that follow a tighter interpretation of MCRpd.

KEY CHARACTERISTICS

The MCRpd interaction model provides a tool for examining several important properties of tangible interfaces. In particular, it is useful to consider the three relationships shared by the physical representations ("rep-p") of TUIs.

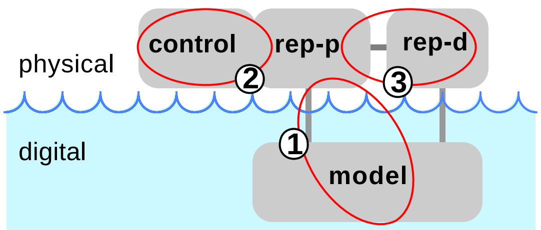


Figure 3: Key characteristics of tangible interfaces

As illustrated in Figure 3, the MCRpd model highlights three key characteristics of tangible interfaces.

1) Physical representations (*rep-p*) are computationally coupled to underlying digital information (*model*).

   The central characteristic of tangible interfaces lies in the coupling of physical representations to underlying digital information and computational models. The Urp example illustrates a range of such couplings, including the binding of graphical geometries (data) to the building objects, computational simulations (operations) to the wind tool, and property modifiers (attributes) to the material wand.

2) Physical representations embody mechanisms for interactive control (*control*).

   The physical representations of TUIs also function as interactive physical controls. The physical movement and rotation of these artifacts, their insertion or attachment to each other, and other manipulations of these physical representations serve as tangible interfaces' primary means for control.

3) Physical representations are perceptually coupled to actively mediated digital representations (*rep-d*).

   Tangible interfaces rely upon a balance between physical and digital representations. While embodied physical elements play a central, defining role in the representation and control of TUIs, digital representations – especially, graphics and audio – often present much of the dynamic information processed by the underlying computational system.

Where the above three characteristics refer directly to our MCRpd model, a fourth TUI characteristic is also significant.

4) The physical state of interface artifacts partially embodies the digital state of the system.

As illustrated in Figure 3, the MCRpd model does not specify whether a TUI's physical representations are composed of one or many physical artifacts. In practice, tangible interfaces are generally built from *systems* of physical artifacts. Taken together, these collections of objects have several important properties. As physical elements, TUI artifacts are *persistent* – they cannot be spontaneously called into or banished from existence. Where a GUI window can be destroyed or duplicated at the touch of a button, the same is not true of Urp's building objects. Also, TUI artifacts frequently may be "read" both by people and computers by their *physical state*, with their physical configurations tightly coupled to the digital state of the systems they represent.

Building from these properties, tangible interfaces often employ systems of multiple objects following one of several major interpretations. In *spatial* approaches, the spatial configurations of physical objects are directly interpreted and augmented by the underlying system. For instance, in the Urp example, the positions and orientations of physical building models map directly into the geographical space of the urban simulation, and are then computationally augmented with graphical shadows, wind interactions, and so forth.

In addition to spatial approaches, several other interpretations are possible. In *relational* approaches, the sequence, adjacencies, or other logical relationships between systems of physical objects are mapped to computational interpretations. In the next section, we will present an example system that was inspired by the Scrabble™ game's tile racks. A third approach involves the *constructive* assembly of modular interface elements, often connected together mechanically in fashions analogous (and sometimes quite literal) to the classic LEGO™ system of modular bricks.

EXAMPLE TWO: MEDIABLOCKS

Where the Urp simulator provides a spatial interface for manipulating the arrangement of architectural building, the mediaBlocks system provides a relational interface for logically manipulating more abstract digital information [Ullmer 98]. MediaBlocks are small, digitally tagged blocks, which are dynamically bound to lists of online media elements. The mediaBlocks system is a tangible interface for manipulating collections of these physically embodied videos, images, and other media elements.

MediaBlocks support two major kinds of use. First, they function as capture, transport, and playback mechanisms, supporting the movement of online media between different media devices. Towards this, mediaBlock "slots" are attached to conference room cameras, digital whiteboards, wall displays, printers, and other devices. Inserting a mediaBlock into the slot of a recording device (e.g., a digital whiteboard) triggers the recording of media onto a networked computer, and couples this media to the physical block as a "dynamic binding." Thus, while the block does not actually contain any information other than its digital ID, the block is linked to online information as a kind of physically embodied URL.

Once it is bound to one or more chunks of digital media, a mediaBlock may be inserted into the slot of a playback device (e.g., a printer or video display) to activate playback of the associated media. Alternately, inserting the block into a slot mounted upon the face of a computer monitor allows mediaBlock contents to be exchanged with traditional computer applications using GUI drag-and-drop.

The system's second major function allows mediaBlocks to function as both media containers and controls on a sequencing device. A mediaBlock "sequence rack," partially modeled after the tile racks of the Scrabble™ game, allows the contents of multiple adjacent mediaBlocks to be assembled into a single ordered media list and dynamically bound to a new mediaBlock container. Similarly, a "position rack" maps the physical position of a mediaBlock into an indexing operation upon the block's contents. When a mediaBlock is moved to the position rack's left edge, the block's first media element is selected. Moving the block to the rack's right edge accesses the block's last content, with intermediate positions providing access to intermediate elements in the block's internal list of media contents.

Figure 4: mediaBlocks and media sequencer *(©ACM)*

TERMINOLOGY

In the previous sections, we have somewhat loosely used a number of terms like "object," "artifact," and "container." As is common in rapidly evolving research areas, many of the terms in this chapter have not yet reached widespread consensus (including the "tangible user interface" phrase itself). With such a consensus likely to be slow in coming, it is valuable to consider the terminology currently in use, as the choice of names often reflects important underlying assumptions.

"Objects," in the physical sense of the word, are clearly a central concern of tangible interfaces. At the same time, this term has been broadly interpreted in the computer science and HCI communities to mean many things, most having nothing to do with the physical world. Moreover, most physical objects have no connection with tangible interfaces. Therefore, while we often discuss "objects" in the TUI context, it is a somewhat ambiguous term. The term "physical/digital objects" is sometimes used to clarify this ambiguity, highlighting the dual physical/digital aspect of TUI elements.

"Artifacts," carrying the implication of man-made physical objects, offers an alternate term with less prior use in the computer science and HCI communities. However, naturally occurring objects like stones and seashells have been used in a number of tangible interfaces, leaving this term again useful but imprecise.

The "props" term has been used in several related research systems, including Hinckley et al.'s influential "doll's head" neurosurgical interface [Hinckley 94]. However, the props term carries the implication of an element that is somehow peripheral to the core (presumably graphical) user interface. We find this somewhat counter to TUI's emphasis upon physical objects as central elements of the user interface.

"Physical icons" or "phicons," a name we introduced in [Ishii 97] with reference to the GUI "icon" concept, offers another possible descriptor. However, as we discuss in [Ullmer 00], this term also has shortcomings. For one, it faces a dilemma that has been widely discussed in the GUI literature: strictly speaking, many so-called "icons" (and "phicons") are not "iconic," but rather "symbolic" in form. For instance, from the perspective of semiotics (the study of signs and symbols), the physical forms of mediaBlocks are symbolic, and not iconic.

The "tangibles" term refers specifically to the physical elements of tangible interfaces, and to their role in physically representing digital information. Partially inspired by the Marble Answering Machine and other work of Bishop [Crampton Smith 95], it was used in this context with the development of the LogJam video logging and ToonTown audio conferencing systems at Interval Research [Cohen 99, Singer 99]. This term has the advantage of brevity and specificity to the TUI context.

For careful consideration of tangible interfaces, we believe the physical elements of tangible interfaces may be usefully described in terms of "tokens" and "reference frames." We consider *tokens* to be the physically manipulable elements of tangible interfaces, and *reference frames* to be the physical interaction spaces in which these objects are used. For example, we consider the building, wind, clock, and material artifacts of Urp, along with the blocks of mediaBlocks, to be kinds of "tokens." Similarly, we consider the graphically mediated workbench of Urp and the sequencer and slots of mediaBlocks to be examples of "reference frames."

From an applied perspective, symbolic tokens are often used as "containers" for other media (as in mediaBlocks). Similarly, tokens that are used to represent digital operations or functions often serve as "tools" (as in Urp). Where the token and reference frame terms are relatively new to the discussion of tangible interfaces, the "container" and "tool" terms have seen wider use.

We have developed the token and reference frame terms partly from a study of board games, which share interesting properties with tangible interfaces. Games such as Chess, Go, Backgammon, Monopoly™, and Trivial Pursuit™ all can be seen as systems of tokens and reference frames. Like tangible interfaces, these games also use manipulable physical tokens as representations for underlying systems of abstract rules. The physical forms assumed by these tokens and reference frames are widely varying, highly evolved, and tightly coupled to their respective games, to the extent that none of the above games could be played with the physical "equipment" of another. These characteristics illustrate the critical role of physical representation in within these games. Several board games also illustrate how tokens can themselves serve as "nested" reference frames, as with the "pies" and "pie wedges" of Trivial Pursuit™.

Several other alternative classifications have been proposed. For instance, Holmquist, Redström, and Ljungstrand suggest the terms "tokens," "containers," and "tools" as classifications for physical/digital objects [Holmquist 99]. Their concept of "containers" and "tools" is similar to our own, while their use of "token" approximates our "iconic tokens" and "phicons." Alternately, Underkoffler presents a "continuum of object meanings," with objects interpreted as reconfigurable tools, verbs, nouns, attributes, and "pure objects" [Underkoffler 99a]. Both of these proposals are useful for their useage-oriented classifications.

COUPLING OBJECTS WITH DIGITAL INFORMATION

In the previous sections, we have introduced several TUI examples and presented the beginnings of a conceptual framework centering on the MCRpd model. In this section, we will consider several elements of MCRpd more carefully, focusing on the ways that TUIs couple physical objects with digital information. First, we will consider MCRpd's *model* aspect, discussing the kinds of digital information that can be associated with TUI artifacts. Next, we will explore the *control* issues of how physical/digital bindings are established and invoked. Finally, we will discuss the kinds of *physical representation* that TUIs may employ, and some of the technical mechanisms by which they operate.

Kinds of digital bindings

The Urp and mediaBlocks examples have illustrated several different kinds of digital associations for TUI artifacts. In Urp, physical building models are coupled to 3D graphical geometries. The material wand is coupled to several material properties ("brick" and "glass"), which may be bound to buildings to invoke graphical shadows and reflections. The wind tool is coupled to a fluid-flow simulation, while the clock tool is coupled to the system's model of time.

The mediaBlocks example introduces several contrasting approaches. The blocks themselves represent a kind of simple data structure – in particular, a list of media elements. The system enables blocks to "contain" lists of images, video, audio, and by implication, any information that can be referenced by a URL. The system also demonstrates blocks embodying "conduits" to remote devices (e.g., a remote printer), and suggested how these conduits might be used as "sources" and "sinks" for live audio, video, and other streaming media. In parallel, physical racks, slots, and pads are mapped to digital operations for connecting mediaBlocks to a variety of media sources and sinks.

As these examples suggest, tangible interfaces afford a wide variety of associations between physical objects and digital information. These associations include:

- static digital media, such as images and 3D models;
- dynamic digital media, such as live video and dynamic graphics;
- digital attributes, such as color or other material properties;
- computational operations and applications;
- simple data structures, such as lists or trees of media objects;
- complex data structures, such as combinations of data, operations, and attributes;
- remote people, places, and things (including other electronic devices).

As a simple example, a TUI might couple a physical token to a simple digital file. For example, we have described how a mediaBlock can "contain" a digital image. In this case, it is clear that the mediaBlocks' "associations" are indeed "digital information."

However, as another example, a TUI token could also represent a remote person, perhaps mediating this at different times through live audio, video, or other means. Technically, the token's audio or video connection is likely to depend on the transfer of "digital information." But conceptually, the user of a successful system may prefer to think of the token as simply representing "John" (or whatever other person or group of people is associated with the object). Such associations, which stretch the notion of "digital information," strike us as some of the most interesting couplings for tangible interfaces.

Methods of coupling objects with information

How does digital information become coupled to physical objects? Again, the Urp and mediaBlocks examples suggest several possibilities. In Urp, building models are statically coupled to building geometries. This basic object/geometry binding cannot be changed within the tangible interface itself; the relationship is assumed to be either specified by the system's designer, or assigned in some other fashion "out of band" from the tangible interface's core physical interaction.

Similarly, the assignment of digital functions to Urp's other artifacts (the material, clock, and wind tools) are statically bound by the system's designer. However, interactions between these artifacts are used to establish dynamic bindings. This is most notable with the use of the material wand, but is also used in other parts of the system (e.g., use of a distance-measuring tool, which is used to link pairs of interface objects).

In contrast, the mediaBlocks system centers upon the establishment of dynamic bindings between digital contents and physical containers. This binding is performed in several ways. As we have described, mediaBlock slots are used both to bind media "into" the blocks (e.g., as a recording from a digital whiteboard), as well as to retrieve a mediaBlock's prior associations (e.g., as media playback onto a printer or screen). Where these examples illustrate the establishment of bindings without use of a "computer" per se, the monitor slot provides a bridge between mediaBlocks and the drag-and-drop "bindings" of the traditional GUI world. In addition, the sequencer racks provide another mechanism for accessing media contents, as well as expressing new mediaBlock bindings in concert with other TUI elements such as the sequencer's target pad.

Approaches to physical representation

The design and selection of appropriate physical representations is a very important aspect of tangible interface design. The disciplines of graphic design, industrial design, architecture, and even furniture and environmental design all hold strong relevance to this task.

However, relatively few tangible interfaces have been strongly shaped by industrial design and other traditional design perspectives. One common approach involves the use of "found objects" – pre-existing objects that are perhaps embedded with position sensors or ID tags, and recontextualized to take on roles within tangible interfaces. For instance, in Hinckley et al.'s neurosurgical interface, a doll's head (and later, a rubber ball) was embedded with position trackers, and used as a physical representation of the human brain [Hinckley 94]. Manipulation of this object controlled the orientation and zooming of a screen-based neurosurgical visualization. Use of the doll's head/ball in combination with a clear acrylic plane invoked and controlled a cross-section view, while a probe object physically expressed the prospective trajectory of a surgical incision.

Another common TUI approach might be described as engineering-driven design. Unlike the software-centric world of graphical interfaces, tangible interface design often hinges on the engineering of custom electronics and mechanics. Often, the design of tangible interfaces has been driven first by the pragmatics of electronic and mechanical design, with conceptual and aesthetic issues of physical form taking a lower priority. Sometimes, this results in bare electronic or mechanical elements being put forward as completed TUI artifacts, often resulting in interfaces that fall short from the standpoint of physical representation and "good design."

A third approach is to center design around the physical artifacts underlying pre-existing workplace practices. For instance, Mackay et al. identified the physical "flight strips" used for managing air traffic in European aircraft control towers as compelling artifacts, and developed computational interfaces augmenting these objects [Mackay 98]. Similarly, McGee et al. have developed PostIt™-based interfaces in military command posts which add computational support to existing command-post practices [McGee 00]. While these efforts can also be viewed as augmented reality systems, their usage of physical objects as computationally mediated artifacts also holds much in common with tangible interface approaches.

Some tangible interfaces have been motivated primarily by concerns for physical representation and design. For example, Oba's Environment Audio concept design used elegantly crafted wooden, metal, and plastic tokens as containers for ambient sounds from nature, urban spaces, and the electronic airwaves, respectively [Oba 90]. This work emphasized the use of physical materials and forms to evoke digital contents. Bishop's influential Marble Answering Machine concept sketch illustrated the use of physical marbles as containers and controls for manipulating voice messages [Crampton Smith 95]. This piece, along with Bishop's accompanying studies, provided one of the earliest illustrations for interlinking systems of physical products through a shared physical/digital "language."

All of these design approaches reflect a tension between interface functionality, "legibility," pragmatics, and aesthetics. Speaking of such issues, the Encyclopedia Britannica notes that "as with some other arts, the practice of architecture embraces both aesthetic and utilitarian ends that may be distinguished but not separated, and the relative weight given to each can vary widely from work to work" [Britannica 00]. We believe that this assessment also applies to the design of tangible interfaces.

Technical realization of physical/digital bindings

The function of tangible interfaces hinges upon the ability to computationally mediate people's interaction with physical objects. While the technical implementation underlying such capabilities goes well beyond the scope of this chapter, a brief flavor of the relevant technologies is useful. From a sensing standpoint, some of the most long-standing approaches include position trackers (often using technologies targeted at virtual reality applications), computer vision, and custom electronics. Over the last decade, the use of wired and wireless ID tag technologies has grown increasingly popular. In particular, RF-ID tags (wireless radio frequency identification tags) have shown special promise.

From an actuation and display standpoint, some of the earliest approaches have relied upon embedded LEDs, speakers, and traditional computer monitors. Beginning with Wellner's pioneering DigitalDesk [Wellner 91], a growing number of interfaces began to use front- or back-projected graphical workbenches. This trend has been accelerated by the rapid progress of video projector technologies. Similar advances in flat panel display technology have driven increased use of embedded flat panels in TUI designs. Motors and other actuation and force-feedback devices are also making inroads into TUI design.

INTERPRETING SYSTEMS OF OBJECTS

As we have discussed in the context of TUI's fourth key characteristic, tangible interfaces tend to combine systems of physical objects in one (or more) of three major interpretations: spatial, relational, and constructive. In [Ullmer 00], we categorized 39 example systems in terms of these approaches. In addition, we identified a number of properties that cluster within these categories.

Here, we will present an overview and illustrative examples of these categories. We do not propose our categories as a formal taxonomy, although they may lend support to such efforts. Instead, our goal is to use these categories as a means for understanding and characterizing diverse systems as part of a cohesive stream of research.

Spatial systems

In *spatial* approaches, the spatial configuration of physical tokens within one or more physical reference frames is directly interpreted and augmented by the underlying system. For example, the positions and orientations of Urp's physical building models map directly into the geographical space of the urban simulation, and are then complemented with graphical shadows, wind interactions, and so forth.

We have also spoken of Hinckley et al.'s neurosurgical interface, in which brain, cutting plane, and surgical props are used to drive a visualization task. Where Urp's system of tokens remain on its horizontal planar workbench when in use, the neurosurgical props are held in "free space" by the user's two hands. Since the spatial relationships between these props are mapped directly into the system's visualization, we also consider this a spatial interface approach.

Relational systems

Spatial approaches tend to use distances, orientations, and Cartesian displacements between physical tokens as key interface parameters. In contrast, *relational* approaches map the sequences, adjacencies, and other logical relationships between tokens onto more abstract computational interpretations. For instance, in the mediaBlocks system, we have discussed ways in which the docking of blocks and slots are used to establish dynamic bindings, and in which racks are used to aggregate or disaggregate block "contents" as a function of their sequence or relative position. We have also briefly described Bishop's Marble Answering Machine, a relational interface where marbles are moved between active surfaces to replay marble contents, redial a marble message's caller, or store the message for future reference.

Another particularly interesting relational interface example is the Slot Machine of Perlman, an interface for controlling LOGO's robotic and screen-based "Turtle" [Perlman 76]. In this interface, sequences of physical "action," "number," "variable," and "conditional" cards were configured within several colored horizontal slots to construct LOGO programs. Multiple cards could be stacked upon one another to create composite commands. E.g., the number card for "4" could be stacked upon the action card for "move forward" to express "move forward 4." Number cards were physically shorter than action cards, allowing all of the card stack's elements to remain visible.

Among many interesting features, the Slot Machine's approach for physically expressing recursion is particularly intriguing. A red "action" card carried the meaning "run the commands in the red slot," and so on for the blue and green slots. In this way, a red card used in the red slot represented a recursive command. When combined with a variable card, for instance, the procedure for drawing a spiral could be compactly expressed.

These examples suggest the possibilities for rich physical/digital languages, especially for interfaces that already depend upon collections of physical-world objects or devices. At the same time, such systems require a careful balance between physical and graphical expression to avoid physical clutter, and to take advantage of the contrasting strengths of different representational forms. This balance between physical and digital representations stands as one of TUI's greatest design challenges.

Constructive systems

A third approach involves the *constructive* assembly of modular elements, often connected together mechanically in fashions analogous (and sometimes quite literal) to the classic LEGO™ assemblies of modular bricks. For instance, in the work of Anagnostou et al. (ca. 1989) and Frazer et al. (ca. 1983), a series of interconnecting cubes were used to describe fluid-flow simulations, 3D cellular automata, and other computational simulations [Anagnostou 89, Frazer 94].

Even earlier efforts in this area were initiated in 1979 by Aish, who described and later implemented a computational "building block systems" for the architecture domain [Aish 79]. Aish imagined that this system might allow lay users to explore and respond to complex factors such as a building's simulated energy consumption early in the architectural design process. More recently, Anderson et al. have designed new implementations and applications for similar systems of blocks, focusing on the integration of "tangible interaction + graphical interpretation" [Anderson 00]. A number of systems have also been built directly upon the LEGO™ bricks platform, including the longstanding work of Resnick et al. [Resnick 98].

Mixed constructive/relational systems

The classifications of spatial, relational, and constructive systems are not mutually exclusive. For example, one promising space lies at the intersection between constructive and relational approaches. Like their constructive kin, these systems tend to be composed of modular, mechanically interconnecting elements. Also like relational systems, these modules and the relationships between them are frequently bound with abstract computational semantics.

One early system in this area is AlgoBlock, a system of cubical aluminum blocks that is related in function to Perlman's Slot Machine [Suzuki 93]. Like the Slot Machine, AlgoBlock was used to physically express a LOGO-like language. Unlike the Slot Machine, AlgoBlock consisted of an array of cubes that dock with each other on a table. Where the Slot Machine stacked "number cards" upon "action cards" to express commands like "ROTATE LEFT BY 45°", each AlgoBlock represented a command, and offered control of associated parameters through knobs and levers permanently embedded within each block. AlgoBlocks also contained lighted buttons to trigger the execution of each physically embodied command. This execution would propagate onwards to other connected blocks, with the lights glowing to indicate the program execution's progression and evolving state.

Another interface with both constructive and relational characteristics is Triangles, a system of triangular acrylic tiles intended for use as a kind of physical/digital interaction toolkit [Gorbet 98]. Triangles interconnect physically and digitally through magnetic hinging connectors. Each contains an embedded micro-controller and unique ID, allowing individual tiles to be associated with specific data or operations. As an example application, "Cinderella 2000" associated Triangles with characters and places from the Cinderella story in a kind of reactive "audio comic book." Connecting the "stepmother" tile to the "Cinderella's home" tile triggered the stepmother's audio recounting of Cinderella's inadequate housework; attaching Cinderella's tile would then invoke a scripted dialog between Cinderella and the stepmother.

It is worth noting that both the AlgoBlock and Triangles interfaces, along with many other systems in the constructive+relational category, have been oriented towards use by children in educational contexts. The authors of these systems have emphasized the ability of physical artifacts to support collaboration between multiple users, and to deliver concrete representations of abstract concepts with special value in educational contexts.

APPLICATION DOMAINS

What kinds of tasks are tangible interfaces good for? Beyond the broad generalizations and point examples we have discussed, several particular applications domains have begun to emerge.

Information storage, retrieval, and manipulation:

One of the largest classes of TUI applications is the use of tangibles as manipulable containers for digital media. The mediaBlocks, Marble Answering Machine, LogJam, and ToonTown examples all illustrate this kind of usage. These systems seem to hold special potential for mediating interaction within and among networked "information appliances."

Information visualization:

TUIs broadly relate to the intersection of computation and "external cognition." As such, they share common ground with the area of information visualization. TUIs offer the potential for rich multimodal representation and input, often providing increased specialization at the cost of general-purpose flexibility. The Urp and neurosurgical props interfaces both offer good illustrations of this application domain.

Modeling and simulation:

Many spatial interfaces and the whole category of constructive interfaces illustrate the use of computationally enhanced cubes, blocks, and tiles as primitive units for modeling and simulating mixed physical/digital systems. Urp, AlgoBlock, the cubes of Frazer and Anagnostou et al., and the bricks of Aish and Anderson et al. illustrate such approaches.

Systems management, configuration, and control:

Several tangible interfaces illustrate the broad capacity for manipulating and controlling complex systems such as video networks, industrial plants, etc. Example interfaces include mediaBlocks, AlgoBlock, ToonTown, and LogJam.

Education, entertainment, and programming systems:

A number of tangible interfaces have demonstrated techniques for programming, most commonly in the context of concretely demonstrating abstract concepts in elementary education. Examples include the Slot Machine, AlgoBlock, Triangles, and the work of Resnick et al. Interestingly, many of these systems are also perceived as holding entertainment value, which perhaps contributes to their prospects for educational use.

While all of these domains represent areas where computers are broadly known to be useful, tangible interfaces are distinguished by a number of special properties. For instance, TUIs are intrinsically well suited to collocated cooperative work by virtue of their many loci of physical control. This contrasts clearly with traditional GUIs, where multiple users must share a single keyboard and pointing device. This property also contrasts with augmented reality and wearable computing systems based upon head-mounted displays, which limit the computer's displays to the viewing space of individual users. Tangible interfaces' externalization of information into physical, manipulable forms also has important implications for facilitating communications and "transparency" of interaction between multiple collocated users.

These properties illustrate ways in which tangible interfaces can leverage lessons from distributed cognition, as discussed within Chapter 5. Distributed cognition describes the roles played by physical objects and the physical environment in supporting memory, learning, and interpersonal communications – all properties of direct relevance to tangible interfaces. The related concept of "physical affordances" also speaks to people's ability to creatively combine physical objects in unexpected fashions – e.g., to use a bowl for holding soup, peas, rubber bands, or floppy disks, or more whimsically, as a hat or boat. Despite the flexibility of graphical interfaces, their support for such recombinations is comparatively quite rudimentary and brittle. Building on the strength of their embodied physical affordances, tangible interfaces hold the potential to support truly creative and spontaneous physical/digital combinations.

RELATED AREAS

Broad context

Humans are clearly no newcomers to interaction with the physical world, or to the process of associating symbolic function and relationships with physical artifacts. We have referenced the abacus example earlier in this chapter, which we have considered in the context of other historic scientific instruments within [Ishii 97].

We have also discussed traditional games of reasoning and chance as presenting interesting case examples. In prototypical instances such as chess and cribbage, we find systems of physical objects – i.e., the playing pieces, boards, and cards – coupled with the abstract rules these artifacts symbolically represent. The broader space of board, card, and tile games, considered as systems of tokens and reference frames, provides an interesting conceptual parallel and grounding for modeling TUIs.

Map rooms, "war rooms," and control rooms offer other examples of the symbolic and iconic uses of physical artifacts. Magnet boards and LEGO boards are sometimes used with reconfigurable tokens for groups to collaboratively track and explore time-evolving processes (we know of such instances in dairies and graduate schools). Within domestic contexts, people use souvenirs and heirlooms as representations of personal histories.

The disciplines of cognitive science and psychology are concerned in part with "external representations." These are defined as "knowledge and structure in the environment, as physical symbols, objects, or dimensions, and as external rules, constraints, or relations embedded in physical configurations" [Zhang 97]. These and other theories and experiments, including analyses of the cognitive role of physical constraints in tasks like the Towers of Hanoi game, seem closely applicable to tangible user interfaces.

As we have discussed, ideas about affordances by Gibson, Norman, and others have long been of interest to the HCI community, and hold special relevance to tangible interface design. Related studies of spatial representation and bimanual manipulation (most notably, by Guiard) also hold special applicability for TUIs. The doctoral theses of Fitzmaurice and Hinckley have offered both perceptive analyses of this literature, as well as contributing new studies in these areas.

The discipline of semiotics – the study of signs and symbols – is concerned in part with the symbolic role of physical objects. We have discussed Peircian semiotics in the context of GUI icons and TUI phicons within [Ullmer 00]. Additionally, semioticians Krampen, Rossi-Landi, Prieto, Moles, Boudon, and von Uexkull have considered the relation of physical tools to human language, grammars, and semantics. We believe these studies may bear strong relevance for TUI design.

HCI context

Shneiderman's three principles of "direct manipulation" [Shneiderman 83], while posed in the context of graphical interfaces, are also directly applicable to tangible interfaces. The first principle – "continuous representation of the object of interest" – knits especially well with the persistent nature of TUI tangibles. As such, the sizable literature relating to direct manipulation, and associated analyses of topics such as perceptual distance, are broadly relevant to TUI design. As with other direct manipulation interfaces, TUIs can be said to cultivate tool-like, rather than language-like, modalities of interaction. At the same time, tangible interfaces are also subject to some of the criticisms that have been directed at direct manipulation approaches, including those discussed in [Frohlich 97].

The area of visual programming languages holds relevance for TUIs. Here, principles such as the "Deutsch Limit," which suggests the implausibility of more than 50 visual primitives in simultaneous use on the screen, may have analogues for TUI systems of physical primitives. At the same time, people's homes and workplaces routinely hold and (at least loosely) structure human interactions with many thousands of objects. While these complex physical environments point to the real challenge of physical clutter and lost objects, they also indicate the richness, power, and flexibility of physical space.

The areas of augmented reality, mixed reality, and ubiquitous computing hold the closest relation to tangible interfaces among existing major research streams. While these areas hold in common a concern for physically contextualized interaction, we believe they inhabit different conceptual and design spaces than tangible interfaces. In particular, where tangible interfaces are centrally concerned with the user interface properties of systems of representational physical artifacts, none of these alternate frameworks share this emphasis.

Different researchers associate widely divergent interpretations of these terms. For instance, where many researchers consider augmented reality to be closely associated with the use of head-mounted displays, others hold a view of augmented reality much closer to our discussion of tangible interfaces. We do not believe these alternate stances are inconsistent, but instead offer different conceptual frameworks, different perspectives and insights, and different points of leverage for considering new kinds of physically embodied user interfaces.

The area of ubiquitous computing, as discussed in Chapter 24, also holds common ground with tangible interfaces. Weiser's vision of ubiquitous computing [Weiser 91], and particularly his concern for bringing computation into niche physical contexts, has strongly influenced TUI research. From a user interface standpoint, the individual devices of ubiquitous computing systems have tended to follow traditional GUI approaches. At the same time, UbiComp's more evolutionary user interface trajectory gives it heightened practical relevance in the immediate term.

CONCLUSION

In this chapter, we have presented steps towards a conceptual framework for tangible user interfaces. We have introduced an interaction model and key characteristics, and applied these to a number of example interfaces. These have included not only systems explicitly conceived as "tangible interfaces," but more broadly numerous past and contemporary systems that may be productively considered in terms of tangible interface characteristics. While these examples illustrate considerable diversity, we believe they also share a number of basic properties and common approaches, which we have begun to generalize into a unifying conceptual framework.

In discussing a broad topic within limited space, we have necessarily left a great many concerns for future consideration. From an HCI standpoint, these include issues of cognitive engagement and distance, general vs. special purpose approaches, and many others. From an engineering perspective, issues include tagging and tracking technologies, hardware and software architectures, prototyping, toolkits, and beyond. And from a design viewpoint, among a great many particular challenges, there is also a more fundamental one: what makes for good tangible interface design? As Underkoffler writes in [Underkoffler 99b], "the future of reactive, real-world graphics will surely have its own Rands and Tuftes, Leacocks and Gilliams." We find this analogy – and even more so, the prospects it raises – highly compelling.

In preparing this chapter, we were both humbled and inspired by Halasz's landmark "Seven Issues" hypermedia paper and "'Seven Issues' Revisited" address. Reflecting on his paper after several years, Halasz remarked that "the Seven Issues paper, in retrospect, takes a very simple and narrow view of what the world of hypermedia encompasses, what was of interest to us as hypermedia researchers" [Halasz 91]. Expanding on this theme, Halasz reflected on the diversity of the hypermedia community – ranging from the divergent interests of literary and technologist practitioners, to differing notions of what constitutes a link, to the contrasting metrics of success in academia and industry.

Again speaking in 1991, Halasz said "One of the main selling points of hypermedia [relates to] very large document collections [10K-100K documents]… Unfortunately, reality has yet to catch up to the vision" [Halasz 91]. From the perspective of the year 2000, Halasz's words offer a breathtaking reminder of how quickly realities can change, and how profoundly long-latent visions can blossom.

While the areas of hypermedia and tangible interfaces are very different in character, Halasz's experiences with unexpected diversity provide an interesting benchmark. For tangible interfaces, who is the community of developers, and what are the dimensions of its diversity?

Our experience suggests this must include practitioners of computer science and cognitive science, mechanical engineering and electrical engineering, art and design, academia and industry. The fusion of physical and digital worlds provides for an extraordinarily rich, and sparsely populated, design space. We look forward to joining with others in exploring the bounds of its potential.

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