Designing for Gesture and Tangible Interaction

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Designing for Gesture and Tangible Interaction

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SYNTHESIS LECTURES ON HUMAN-CENTERED INTERACTION #36

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ABSTRACT

Interactive technology is increasingly integrated with physical objects that do not have a traditional keyboard and mouse style of interaction, and many do not even have a display. These objects require new approaches to interaction design, referred to as post-WIMP (Windows, Icons, Menus, and Pointer) or as embodied interaction design.

This book provides an overview of the design opportunities and issues associated with two embodied interaction modalities that allow us to leave the traditional keyboard behind: tangible and gesture interaction. We explore the issues in designing for this new age of interaction by highlighting the significance and contexts for these modalities. We explore the design of tangible interaction with a reconceptualization of the traditional keyboard as a Tangible Keyboard, and the design of interactive three-dimensional (3D) models as Tangible Models. We explore the design of gesture interaction through the design of gesture-base commands for a walk-up-and-use information display, and through the design of a gesture-based dialogue for *the willful marionette*. We conclude with design principles for tangible and gesture interaction and a call for research on the cognitive effects of these modalities.

KEYWORDS

embodied interaction, gesture interaction, tangible interaction, interaction design, cognitive effects

Contents

Preface

This book reflects on the significance and design of embodied interaction with digital information and artifacts. We are experiencing a transition from traditional modes of interacting with computing devices in which we are typically sitting still and moving our fingers on a keyboard to large body movements to effect changes and engage with digital information and artifacts. As designers we are challenged not only by the increasing range of technologies that enable interaction design, but also by the range and focus on human-centered design methodologies. Engineering design starts with requirements derived from human needs but necessarily has a focus on the design of the system so that it satisfies those requirements and optimizes performance of the system. In contrast, in interaction design, the human is inherent to the system and therefor the focus remains on human needs, desires, and abilities throughout the design process. Along with this focus on people during the design of interactive systems, there is an opportunity to move beyond human factors and physical considerations to consider the social and cognitive effects of alternative designs. These opportunities create a new era in interaction design that includes such things as designing gestures and a stronger focus on physical and digital affordances and metaphors. This book is a starting point for understanding the significance of this transition and is a harbinger for future interaction designs in which large body movements are the basis for interaction. Not only is embodied interaction creating new modalities for interaction, it is also redefining the focus of good interaction design by moving away from efficiency and productivity as the basis for interaction design toward the inclusion of creativity and social interaction in the goals for new designs.

Mary Lou Maher and Lina Lee
January 2017

Acknowledgments

This book is a reflection on our collaboration with many colleagues whose views and ideas are tightly woven within our understanding of tangible and gesture interaction. After many years of collaboration, it is hard to untangle our thoughts from the engaging discussions about tangible and gesture interaction. We acknowledge our colleagues here as an integral part of our ability to produce this book. Our understanding of tangible interaction design and our design examples, Tangible Keyboard and Tangible Models, were influenced by Tim Clausner, Mijeong Kim, Alberto Gonzalez, and Kaz Grace. Our understanding of gesture interaction design and our design examples, walk-up-and-use information display and *the willful marionette*, were influenced by collaboration with our artists in residence, Lilla LoCurto and Bill Outcault, and our colleagues Kaz Grace and Mohammad Mahzoon. Lilla and Bill are the artisits that imagined, created, and built *the willful marionette*.

Completing this book was possible only with the patience of our families. Our special thanks go to the babies born during this writing project and the many sleepless nights we experienced. We particularly acknowledge the birth of Jessica, Kei, Iris, Matthew, and Erin during the time we were writing this book.

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January 2017

CHAPTER 1

Introduction

In this book we explore the design issues for embodied interaction design, and specifically for tangible and gesture interaction. This book describes engaging ways of interacting with tangible and gesture-based interactive systems through four different examples as vehicles for exploring the design issues and methods relevant to embodied interaction design. In recent years, new interaction styles have emerged. Researchers in human-computer interaction (HCI) have explored an embodied interaction that seeks to explain bodily action, human experiences, and physicality in the context of interaction with computational technology (Antle et al., 2009, 2011; Klemmer et al., 2006). Dourish (2004) set out a theoretical foundation of embodiment. The concept of embodiment in tangible user interfaces (TUIs) describes how physical objects may be used simultaneously as input and output for computational processes. Similarly, in gesture-based interaction the concept of embodiment recognizes and takes advantage of the fact that humans have bodies, and people can use those bodies when interacting with technology in the same ways they use them in the natural physical world (Antle et al., 2011). This is an attractive approach to interaction design because it relates to our previous experience and makes it easier to learn new systems.

The success of interaction design depends on providing appropriate methods for the task at hand that improve discoverability and learnability. Designers should consider the user's mental model based on previous experience when defining how the user can interact with the system, and then give the user clues about expected behavior before they take action. Giving feedback to the users is important to make it clear how the user completes an interaction. Since interaction is a conversation between the user(s) and the system, interaction design for gesture input methods and real-time feedback to the user(s) should be very carefully considered. Well-timed, appropriate feedback helps users to notice and understand that the system is interactive, to learn how to interact with it, and to be motivated to interact with it. Ideally, feedback communicates to the user that the system status has altered as the user intended (Dillon, 2003).

As we move toward embodied interaction, we maintain these basic principles of good interaction design: the user initiates interaction with some form of action, and the system responds or alters as the user intended. However, the trend for embodied interaction is the design of very broad and varied ways in which the user is expected to act to initiate interaction, and the iterative action-response needs to be discovered and learned. For example, laptop and touchscreen interactions are ubiquitous enough that there are established guidelines and design patterns that designers adhere to (Norman, 1983). These patterns and guidelines cause users to have certain expectations of how a system might work even before they begin interacting with it. However, embodied interaction is relatively new and does not have as coherent a set of consistent design patterns for interaction. Therefore, we transition from an expectation for consistent and effective interaction design using keyboard, mouse, and display, toward novel interactive systems in which the user explores and learns which actions lead to expected changes in the state of the system. We propose that HCI is a cognitive process in which the user mental model is the basis for their exploration and use of the interactive system. Users decide how to interact on the basis of expectation and prior experience, and the affordances of the specific interactive system modify the user mental model.

As Dourish (2001) says, when users approach an embodied interactive system, they must construct a new understanding of how it works on the basis of their physical exploration. Different people may have unique experiences and expectations, which will affect the way in which they initially explore a system and, ultimately, the mental model they construct of how the system works (Dillon, 2003). Embodied interaction has been used to describe the interactions of users with a wide range of interactive technologies, including tangible and gesture-based interfaces.

We posit that good tangible and gesture interaction design depends on an understanding of the cognitive issues associated with these modalities. We organize these issues into four categories: embodiment, affordances, metaphor, and epistemic actions. These four categories can be used as clues that the designer can give the user to aid the user in understanding how the interactive system is to be operated. If these concepts are integrated into the design process, the user's mental model and knowledge can be activated and extended as they try to use and understand the interactive system. While these cognitive issues require further exploration and empirical validation (Antle et al., 2011), we present specific projects that explore various aspects of embodied HCI.

1.1 EMBODIMENT

Interaction through tangible and gesture-based systems is intrinsically embodied, and therefore decisions about which embodied actions can be recognized by the interactive system are part of the design process. Human gestures are expressive body motions involving physical movements of the fingers, hands, arms, head, face, or body that may convey meaningful information or be performed to interact with the environment (Dan and Mohod, 2014). Designing embodied interaction is not just about designing computing ability, but is also about designing the human experience and anticipated human behavior.

Research has shown that gestures play an integral role in human cognition. Psychologists and cognitive scientists have explored the role of gesture and thought for several decades. McNeil (1992, 2008) explains that gesture and thought are tightly connected, and he also establishes a categorization of gestures and their role in human cognition and communication. There is evidence that gesturing aids thinking. Several studies have shown that learning to count is facilitated by touching physical objects (Efron 1941; Kessell and Tversky 2006; Cook et al., 2008). Kessell and Tversky (2006) show that when people are solving and explaining spatial insight problems, gesturing facilitates finding solutions. Goldin-Meadow and Beilock (2010) summarize findings as "gesture influences thought by linking it to action, (p. 669)" and "producing gesture changes thought (p. 670)" and can "create new knowledge (p. 671)." These studies show that gesture, while originally associated with communication, is also related to thinking. Embodied interaction design creates an environment that is activated by gesture and actions on objects and therefore induces cognitive effects that traditional user interaction does not.

One challenge to embodied interaction is that while it is built upon natural actions, it still requires some level of discovery, especially when it is a public display. Tangible and gesture-based interaction designers consider both the integration of technology and its effects on human experience. The major consideration that has emerged to influence tangible design is the physical embodiment of computing. Interaction design is not just screen-based digital interaction anymore. Tangible interaction designers should think about physical, graspable objects that give cues for understanding and provide the basis for interaction. Gesture interaction designers should think about how various human movements can be recognized and interpreted in the context of changing the state and response of the computational system. Interactive platforms can be interpreted as spaces to act and move in, and they effectively determine interaction patterns.

Dourish (2004) explores the physicality of embodied interaction and its affect on moving human computer interaction toward more social environments. He describes an approach to embodiment grounded in phenomenology, and claims that any understanding we have of the world is the result of some initial physical exploration. Embodied interaction is about establishing meaning and it is through embodied interaction that we develop an understanding of the meaning of the system. As the user constructs their mental model, they are influenced by the phenomena they are experiencing at that moment as well as their prior experiences and understanding of how technology works.

In this book, we take a cognitive view of embodied interaction design: Discovering the interaction model relies on pre-existing mental models derived from physical experiences, and executing intentional physical movements during interaction has an effect on cognition. We demonstrate and elaborate on this view of embodiment through four projects; where we describe the gestures that enable interaction, the design methods, and the usability issues for each project.

1.2 AFFORDANCE

The concept of affordance was introduced to the HCI community by Norman (1988) and Gibson (1982). According to Norman (1988), an affordance is the design aspect of an object that allows people to know how to use it and that gives a clue to its function and use. Norman discusses the concept of affordance as properties of an object that allow specific actions such as a handle affords holding and turning, a button affords pressing and make it its own function clear. Tangible interaction design is arguably more influenced by physical affordances than by visual or gesture interaction design.

TUIs change the way we interact with digital information, with physical affordances that are distinctly different from pointing and keyboard/mouse interaction. According to Wang et al. (2002), there are two advantages to tangible interaction; first, it allows direct, naïve manipulability and intuitive understanding; and second, the sense of touch provides an additional dimension. The tactile feedback afforded by TUIs is consistent with the early empiricist argument that kinesthetic information provides us with the ability to construct a spatial map of objects that we touch (Lederman and Klatzky, 1993; Loomis and Lederman, 1986). Fitzmaurice (Fitzmaurice, 1996; Fitzmaurice and Buxton, 1997) demonstrated that having multiple graspable interactive devices encourages two-handed interaction that calls upon everyday coordination skills. Leganchuk et al. (1998) explored the potential benefits of such two-handed input through experimental tasks to find that bimanual manipulation may bring two types of advantages to HCI: manual and cognitive. The two-handed interaction doubles the freedom simultaneously available to the user and reduces the cognitive load of the input performance.

The potential affordances of the TUIs, such as manipulability and physical arrangements, may reduce cognitive load associated with spatial reasoning, thus resulting in enhanced spatial cognition and creative cognition. Brereton and McGarry (2000) studied the role of objects in supporting design thinking as a precursor to designing tangible interaction; they found that design thinking is dependent on gesturing with objects, and recommend that the design of tangible devices consider a tradeoff between exploiting the ambiguous and varied affordances of specific physical objects. The affordances of design tools facilitate specific aspects of designing. As we move away from the traditional WIMP (Windows, Icons, Menus, and Pointer) interaction, we encounter new kinds of affordances in interactive digital design tools (Burlamaqui and Dong, 2015). Tangible interaction design takes advantage of natural physical affordances (Ishii and Ullmer, 1997) by exploiting the knowledge that people already have from their experience with nondigital objects to design novel forms of interacting and discovering. In this book, we focus on the affordances of the interaction that can be sensed by the interactive devices. Well-designed objects make it clear how they work just by looking at them. The successful design of embodied interaction systems does not ignore the affordances of the physical and visual aspects of the system.

1.3 METAPHOR

While affordances of physical objects are closely related to our experience with their physical properties, the properties of tangible interaction objects have both physical and digital relationships. In contrast to physical objects, on-screen objects are clusters of pixels without a physical dimension.

A common way to create the appearance of physical affordances to on screen objects is the use of metaphor in designing interface elements (Szabó, 1995). By creating a visual reference on screen to familiar physical objects, the on-screen objects take on some of the affordances of the metaphorical object (Mohnkern, 1997).

The use of a metaphor during design makes familiar that which is unknown or unfamiliar by connecting it with the user's previous experience (Dillon, 2003). The most well-known is the "desktop metaphor" used in current operating systems. Another common example of metaphor is the trash can. You can grab a file with the mouse to take it above the trash can and release it. A designer can use the shape, the size, the color, the weight, and the texture of the object to invoke any number of metaphorical links (Fishkin, 2004).

Metaphors are an important concept for embodied interaction. An interaction model based on embodied metaphors effectively implements a mapping between action and output that is consistent with the metaphorical object. Through design, we can map human behaviors and bodily experiences onto abstract concepts in interactive environments (Bakker et al., 2012). Metaphor gives users a known model for an unknown system. Metaphor can help ease the transition to a new situation, so it is good for creating systems that will be used primarily by novices, like public displays. For embodied interaction design, in which there are few standards and fewer user manuals, the role of metaphor in design may be critical in creating easily discovered and learnable interactive systems.

1.4 EPISTEMIC ACTIONS

Epistemic action is exploratory motor activity aimed at uncovering information that is hard to compute mentally. Kirsh and Maglio (1994) distinguish between epistemic and pragmatic actions. A pragmatic action is the action needed to actually perform the task. Epistemic actions are actions that help the person explore the task and guide them to the solution. As such, epistemic actions enable the person to use physical objects and their environment to aid their cognition (Kirsh and Maglio, 1994; van den Hoven and Mazalek, 2011). Therefore, having a variety of tangible objects and physical arrangements may aid problem solving while interacting with a tangible interactive system. Fitzmaurice (1996) discussed the concepts of pragmatic and epistemic actions to provide the underlying theoretical support for workable graspable user interfaces (UIs). Pragmatic action refers to performatory motor activity that directs the user toward to the final goal. Epistemic action refers to exploratory motor activity that may uncover hidden information that would otherwise require a great deal of mental computation.

Kim and Maher (2007) found an increase of epistemic actions in a design task while using a tangible UI, and through a protocol analysis, were able to also observe an increase in the cognitive processes typically associated with creative design. The projects in this book build on that result to design tangible interfaces based on physical objects that offer more opportunities for epistemic (i.e., exploratory) actions than pragmatic (i.e., performatory) actions. Exploration through epistemic actions enables a better perception of the environment and supports learning more about the properties of the objects. When designing gesture-based interaction, the process of discovering the interaction model can be leveraged by encouraging and responding to epistemic actions.

1.5 THIS BOOK

In this book we present tangible and gesture interaction design with an underlying assumption that embodiment, affordances, metaphor, and epistemic actions are critical cognitive issues that can influence the quality of the design. If the interaction design is not well conceived with respect to these cognitive issues, users suffer from frustration, discomfort, stress, and fatigue. Applying appropriate design methods is crucial and should help bridge the differences between the designer's view of the system and user's mental model. It is important to conduct user research to know how to incorporate the insights from users' experiences into the design. In this book, various user research and design methods such as gesture elicitation, protocol analysis, heuristic evaluation, prototyping, body-storming, role-playing, personas, and image boards are described to show how designers understand the potential user mental models of the interactive system. We describe these methods in the context of their use in the four design examples: Tangible Keyboard, Tangible Models, walk-up-and-use information display, and *the willful marionette*.

This book can provide HCI practitioners and researchers with new principles for better designs and new ideas for research in embodied interaction. For HCI practitioners, the book describes specific design projects and the methods used during design and evaluation. These methods are specific to designing for tangible and gesture interaction. The description of these methods will help practitioners understand how these methods are applied, and, when appropriate, how these methods are uniquely suited to tangible and gesture interaction. For the HCI researcher, the book identifies the cognitive and design research issues that are raised when designing for tangible and gesture interaction. Many of the methods described in the design projects are also applicable in a research context.

The organization of this book is as follows: Chapter 2 presents the concepts and significance of tangible interaction design. In Chapter 3, we present a description of our experience in designing the Tangible Keyboard and Tangible Models. Gesture interaction design is presented in terms of the technology and significance in Chapter 4. We follow this with a description of our experience in designing the walk-up-and-use information display and *the willful marionette* in Chapter 5. In Chapter 6, we conclude with our understanding of the research challenges in designing for embodied interaction design.

CHAPTER 2

Tangible Interaction Design

2.1 WHAT IS A TANGIBLE INTERACTION?

Tangible User Interfaces (TUIs) have emerged as an interface and interaction style that links the digital and physical worlds (Ullmer and Ishii, 2000; Shaer and Hornecker, 2010). An early definition of tangible interaction was introduced by Ishii and Ullmer (1997) as an extension of the idea of graspable user interfaces (UIs): they argued that tangible interaction allows users to grasp and manipulate bits by coupling digital information with physical objects and architectural surfaces.

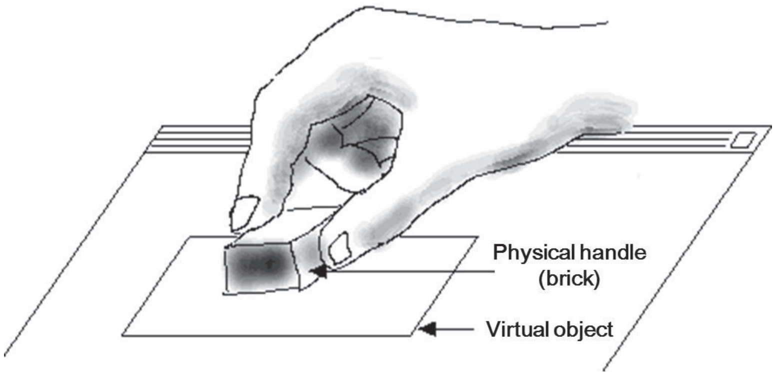

Figure 2.1: Graspable object. Based on Fitzmaurice (1996, p. 4).

TUIs employ physical objects with a direct correlation to digital objects as an alternative to traditional computer input and output devices for control (e.g., mouse) and display (e.g., screen) (Fishkin, 2004). A person uses their hands to manipulate one or more physical objects via gestures and actions such as pointing, clicking, holding, and grasping. A computer system detects the movement, changes its state, and provides feedback (Petridis et al., 2006). TUIs are designed to build on our experience and skills from interacting with the non-digital world (Ishii and Ullmer, 1997; Shaer and Jacob, 2009). TUIs offer the possibility of natural interfaces that are intuitive and enjoyable to use as well as easy to learn (Shaer, 2008). TUIs have the potential to enhance learning and problem solving by changing the way people interact with and leverage digital information (Shaer and Jacob, 2009). Current research in tangible interaction includes understanding the design and cognitive implications of TUIs, developing new technologies that further bridge the digital and the physical, and guiding TUI design with knowledge gained from empirical studies.

The goal of this chapter is to provide an overview and general framework for the design of tangible interaction, including consideration of the role of gesture and the impact on cognition. We believe that TUIs have an impact on cognition because they provide affordances that encourage and facilitate specific gestures and actions, making some cognitive activities easier. TUIs change the way we interact with digital information via physical affordances that are distinctly different from pointing and keyboard/mouse interaction. This chapter explores physical manipulation as an interaction design space. TUIs trigger various gestures and have potential for exploring information through novel forms of interacting and discovering. The chapter presents the concepts and design issues of TUIs through two examples: the Tangible Keyboard and Tangible Models. They exemplify two approaches to integrating TUIs with traditional interaction design: the Tangible Keyboard design examines the metaphor of a keyboard where each key is a tangible object; Tangible Models design examines physical interaction with 3D objects as proxies for 3D digital models.

2.1.1 TANGIBLE KEYBOARD

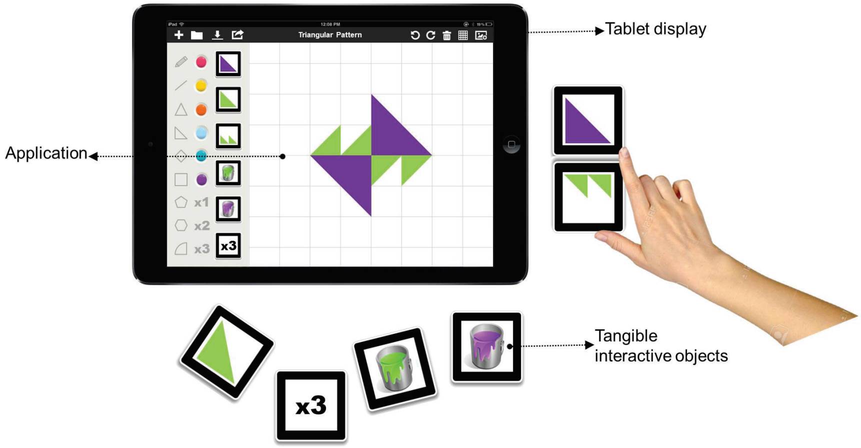

Figure 2.2: Pattern Maker application on the Tangible Keyboard. Tangible Keyboard video available on: https://drive.google.com/file/d/0B4S5ptYjjjuGbFEyX2ljUk90LVU/view?usp=sharing.

Tangible Keyboard is a tangible computing platform that adopts a keyboard metaphor in developing tangible devices for touch screen tablets. The tangible interaction design has a focus on supporting composition tasks and the potential for enhancing creative cognition through spatial arrangement. The Tangible Keyboard design provides separate interaction spaces for composition tasks: the whole composition is displayed on the tablet, and the individual pieces of the composition are manipulated on tangible interactive objects. Individual elements are displayed on tangible interactive objects (inspired by Sifteo cubes™), and these smaller displays are manipulated to create a composition on a larger touch display tablet (Merrill et al., 2012). A variety of different gestures and actions on the tangible objects serve as the basis for the interaction design of the Tangible Keyboard. The larger display on a tablet provides visual feedback for compositions and the touch screen allows users to interact with on-screen content. The affordances of the Tangible Keyboard build on the idea of creating keys, similar to the keys on a keyboard, where the symbols on the keys are interactive, and the keys can be rearranged to create variety of creative patterns. Figure 2.2 illustrates the Tangible Keyboard design with the Pattern Maker application.

2.1.2 TANGIBLE MODELS

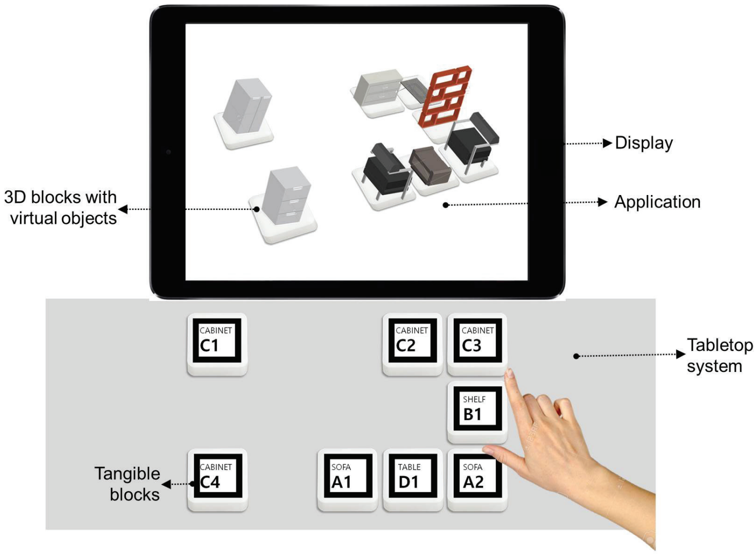

Figure 2.3: Tangible Models interaction design for CAD modeling.

Tangible Models is a tangible computing platform that combines a touchscreen tabletop system with augmented reality that integrates tangible objects on a horizontal display to support 3D configuration design tasks (Kim and Maher, 2008). This tabletop system provides a physical and digital environment for co-located design collaboration. The tabletop system runs a computer-aided design (CAD) program to display a plan view of a 3D design, with physical augmented reality blocks representing objects and their placement on the plan view. Tangible Models interaction design uses 3D blocks with markers that reference 3D models in the ARToolKit (https://artoolkit.org/). Using ArchiCAD (http://www.graphisoft.com/archicad/), Tangible Models allows the user to arrange 3D models from a library, such as walls, doors, and furniture. The ArchiCAD library provides pre-designed 3D objects that can be selected, adapted, and placed in the new design. Tangible Models interaction design comprises selection and rearrangement actions on blocks to explore alternative configuration designs. By rearranging 3D models as physical actions on blocks, the affordances of this UI reduces cognitive load by providing direct manipulability and intuitive understanding of the spatial relationships of the components of the design. Figure 2.3 illustrates the Tangible Models platform using 3D models of furniture from the ArchiCAD library.

2.2 WHY IS TANGIBLE INTERACTION INTERESTING?

TUIs represent a departure from conventional computing by connecting digital information with graspable objects in the physical world (Fishkin, 2004). Fitzmaurice (1996) defines five core properties as the major differences between tangible interaction devices and mouse/keyboard interaction devices:

1. space-multiplexing of both input and output;
2. concurrent access and manipulation of interface components;
3. strong specific devices;
4. spatially-aware computational devices; and
5. spatial re-configurability of devices.

A hallmark of TUIs is specialized physical/digital devices that provide concurrent access to multiple input devices that can control interface widgets as well as afford physical manipulation and spatial arrangement of digital information and models (Fitzmaurice, 1996; Fitzmaurice and Buxton, 1997; Shaer and Hornecker, 2010). These characteristics affect the way tangible interaction is designed. In addition, tangible interaction is contextual: the design is strongly affected by the context of use. The Tangible Keyboard is designed for composition of elements that do not have a corresponding 3D physical object, such as words, numbers, or 2D shapes. The Tangible Models platform is designed for the composition of elements that have a 3D physical counterpart. We explore these 5 factors and their characteristics to better understand design principles for TUI in the context of the Tangible Keyboard and Tangible Models.

2.2.1 SPACE-MULTIPLEXED INPUT AND OUTPUT

Space-multiplexed input and output involves having multiple physical objects, each specific to a function and independently accessible (Ullmer and Ishii, 1997). Time-multiplexed input and output occurs when only one input device is available (for example, the mouse): the user has to repeatedly select and deselect objects and functions (Shaer and Hornecker, 2010). For example, the mouse is used to control different interaction functions such as menu selection, scrolling windows, pointing, and clicking buttons in a time-sequential manner (Jacko, 2012). TUIs are space-multiplexed because they typically provide multiple input devices that are spatially aware or whose location can be sensed by the system. As a result, input and output devices are distributed over space, enabling the user to select a digital object or function by grasping a physical object (Shaer and Hornecker, 2010; Patten and Ishii, 2007).

1) Tangible Keyboard

Tangible Keyboard has space-multiplexed input/output devices, which enables graspable rearrangement of the elements of a composition. This design provides a distinct approach to composition that is not supported by the traditional keyboard or mouse owing to the ability to manually rearrange subsets of a composition and control the content on the subset being manipulated by referring to the composition on a larger display. With space-multiplexed input, each function to be controlled has a dedicated transducer, each occupying its own space (Fitzmaurice and Buxton, 1997). For example, in a Pattern Maker application on the Tangible Keyboard, each cube can be used to manipulate a shape, a color, and a scaling function. While the input devices are used to manipulate and input the composition, they also provide a visualization of subsets of the composition that can be repeated or rearranged as input.

2) Tangible Models

Tangible Models also has space-multiplexed input/output devices. The individual input/output blocks are each associated with a 3D digital model that is visible on the vertical display. The 3D models are rearranged on the tabletop in reference to a plan view of the composition, with visual feedback of the 3D scene on the vertical display. These multiple 3D blocks allow direct control of digital objects as space-multiplexed input devices, each specific to a function and independently accessible. The application of Tangible Models to the configuration design of rooms on a floor plan layout allows the user to assign 3D models such as walls and furniture from a library to each block. The user can rearrange the blocks to explore various design configurations by reaching for and moving the block as a handle for the 3D model.

2.2.2 CONCURRENCY

A core property of TUIs is space-multiplexed input and output. This allows for simultaneous, but independent and potentially persistent selection of objects. TUIs have multiple devices available, and interactions that allow for concurrent access and manipulation of interface components (Fitzmaurice, 1996). In a traditional graphical user interface (GUI), one active selection is possible at a time and a new selection should be done in order to undo a prior one. Time-multiplexed input devices have no physical contextual awareness and lack the efficiency of specialized tools. The ability to use a single device for several tasks is a major benefit of the GUI, but given the nature of interaction, where only one person can edit the model at a time, the GUI environment may change interactivity in collaborative design (Magerkurth and Peter, 2002). However, TUIs can possibly eliminate many of the redundant selection actions and make selections easier. In terms of collaborative interactions, the TUI environment enables designers to collaborate on handling the physical objects more interactively by allowing concurrent access with multiple points of control (Maher and Kim, 2005).

1) Tangible Keyboard

Tangible Keyboard focuses on the user experience during a creative task in which the user has multiple tangible objects that are manipulated to compose and synthesize elements of new design. Multiple tangible objects offer greater flexibility, allowing each input device to display different types of function. In the Pattern Maker application, each input device displays a single shape, color, or scale. A shape can also be modified on a cube by rearranging these different shapes, colors, and scales. Shape cubes can be manipulated independently but also modified with color or scale cubes to create new design patterns. Concurrency is achieved through simultaneous access to multiple physical devices where each one displays its own shape, color, or scale.

2) Tangible Models

Tangible Models provides a similar experience, but with each tangible object assuming the geometric properties of a 3D object. The spatial rearrangement of the 3D models is directly correlated with the 3D composition. Concurrency is achieved through simultaneous access to multiple 3D models, each on a separate physical object. A protocol study of designers using Tangible Models, described in Kim and Maher (2008), showed that users were more focused on the spatial and functional relationships among the individual 3D objects than on the properties of each object when compared to an interaction design that was time-multiplexed (keyboard and mouse). With the direct, naïve manipulability of physical objects and rapid visualization, designers in the TUI environment produced more cognitive actions and completed the design tasks faster.

2.2.3 STRONG SPECIFIC DEVICES

TUIs provide strong specific devices for interacting with the system. This offers more efficiency because the tangible objects are designed to be more specialized and tailored for working on a given task in order to increase the directness and intuitiveness of interactions (Le Goc et al., 2015;

Hornecker, 2005). The design of appropriate physical representations is a very important aspect of tangible interface design (Ullmer and Ishii, 2000). To create strong specific devices, the most common approach is to utilize existing objects into which position sensors or ID tags are inserted. Alternatively, strong specific devices are achieved with Augmented Reality (AR), where each physical device is associated with a virtual object. The user interacts with a virtual object by manipulating the corresponding physical object (Waldner et al., 2006). While seeing virtual imagery superimposed on physical objects, the user perceives interaction with the digital object. These specialized interactive objects may lack generality and therefore may not be effective for some tasks. This loss of generality may be overcome by the advantages provided by task-specific physical tools (Fitzmaurice, 1996). Tangible user interaction with physical objects that have a specialized form and appearance offer affordances normally associated only with the physical object.

1) Tangible Keyboard

In the case of the Tangible Keyboard, the form is constant (cube-like objects with a display) and the appearance (display) is variable. The image on the display is designed to fit the context of the tasks supported by the application. The affordances of these specific devices are those associated with the shape of the object and the content on the display. In the Pattern Maker application, shape cubes are rearranged to form patterns and color cubes are tilted to pour a new color on a shape. These strong specific devices do not have the generality of the mouse for selecting any function, but provide strong feedback on the functions enabled by the application.

2) Tangible Models

With Tangible Models, simple 3D blocks as tangible devices are rearranged on a tabletop system with a vertical display of the 3D scene. Each block is associated with a single 3D model, providing a strong specific device for creating a composition of a scene or spatial design. With static mappings and multiple input objects, 3D blocks as tangible input elements can be expressive and provide affordances specific to the object they represent. The visualization of each 3D block directly indicates its meaning or function while the user is moving the pieces and making a composition.

2.2.4 SPATIALLY AWARE COMPUTATIONAL DEVICES

Spatially aware computational devices and spatial configurations are important concepts in embodied interaction. A physical object in TUIs is typically aware of its spatial position and is registered with a central processing unit. Both position and orientation are critical pieces of information to be sensed (Fitzmaurice, 1996; Valdes et al., 2014). Proximity information is possible through communication to a central processing unit or independent sensors on each device. Applications that are more graphic than alphanumeric benefit from having spatially aware input devices, as graphical tasks are inherently spatial in nature (Fitzmaurice, 1996). Spatially aware computational devices allow users to interact with complex information spaces in a physical way by changing the spatial position and orientation of tangible devices.

1) Tangible Keyboard

Tangible Keyboard is built on the hardware/software platform of Sifteo cubes™ and the sensors include adjacency awareness and accelerometers. These sensors allow the cubes to be aware of other cubes and the movements of each cube, such as shaking, tilting, and turning over. By communicating with a central processor, the rearrangement and movements of the cubes can be mapped onto input events related to the composition task. For the Pattern Maker application, spatial awareness of the individual devices allows the user to form compositions and to modify the shape, color, and scale of elements of the composition.

2) Tangible Models

Tangible Models is built on the software platform of the ARToolkit, in which spatial awareness is achieved by a camera that senses the location of predefined markers (Kato et al., 2001). The assignment of each marker to a 3D model allows the superposition of the visualization of the 3D model on the block. The identification of a marker in the physical space sensed by the camera allows the movement of the block in the physical space to be tracked and visualized in the digital space and displayed on the tabletop for the plan view and on the vertical screen for the perspective view.

2.2.5 SPATIAL RECONFIGURABILITY OF DEVICES

Tangible objects are discrete, spatially reconfigurable physical objects that represent and control digital information. Tangible objects enable reconfiguration, which provides the feeling that users are actually holding and rearranging the information itself. According to Fitzmaurice (1996), the spatial reconfiguration of physical elements such as placement, removal, orientation, and translation are the modes of interaction with tangible interfaces. Those physical controls generally communicate with the surrounding environment and contribute to its overall function and use. The value of discrete, spatially reconfigurable interactive devices goes beyond the value in grasping and rearranging the devices because the physicality of the device serves as a cognitive aid by providing an external cue for a particular function or data item. Users can rapidly reconfigure and rearrange the devices in a workspace and customize their space to suit their own needs in task workflows and task switching (Fitzmaurice, 1996). While this can be achieved in some WIMP interfaces, the use of tangible devices makes this reconfiguration as simple as holding the device and moving it to a new location.

1) Tangible Keyboard

Tangible Keyboard enables configuration of elements within an application or across applications. In the Pattern Maker application, each cube can represent a shape, color, or scale. Within that application, the display and meaning of a specific cube can be changed from a shape to a color to a scale. Across applications, when, for example, comparing the Pattern Maker application to the Silly Poems application, the display on a cube can be changed from a shape to a word. Seeing the Tangible Keyboard, even when it is not being used, conveys an interaction design of physical manipulation and spatial configuration of the physical elements within the interaction design.

2) Tangible Models

Tangible Models enables configuration of models within or across applications. Within an application, the 3D model associated with each block can be changed by selecting another object from the library to assign to a specific block. Across applications, the 3D models available to be selected for each block can be changed by selecting a different library of models. If configuring a structural engineering design, the library would comprise beams, columns, and floor panels instead of furniture and walls. Seeing a Tangible Models device, even when it is not being used, conveys an interaction design of physical manipulation due to the physical presence of blocks on a tabletop system.

2.3 WHAT ARE KEY DESIGN ISSUES FOR TANGIBLE USER INTERFACES?

TUIs show promise to significantly enhance computer-mediated support for a variety of application domains, including learning, problem solving, and entertainment. Also, TUIs offer the possibility of interfaces that are easy to learn and use. However, TUIs are currently considered challenging to design and build owing to a lack of existing software applications that can take advantage of continuous and parallel interactions, the lack of standard interaction models and abstractions for TUIs, and the need to cross disciplinary boundaries to effectively link the physical and digital worlds (Shaer et al., 2004; Shaer and Hornecker, 2010). This section discusses four design issues of TUIs based on Shaer and Jacob (2009);

1. designing interplay of virtual and physical;
2. selecting from multiple gestures and actions;
3. crossing disciplinary boundaries; and
4. the lack of standard input and output interaction models.

Explorations of these design issues provide us with an increasingly clearer picture of the strengths and limitations of TUIs. Good design aims to bring out the strengths and to alleviate weaknesses. In this section, we discuss some of the design issues of TUIs. However, it is important to note that TUI research is a growing and rapidly evolving field, and our understanding of the implications of TUI design requires further investigation. Building a TUI is a complex process that encompasses multidisciplinary knowledge, including computer science, design, and cognitive sciences. Many researchers and interaction designers have introduced a variety of techniques for designing and building novel TUIs. However, TUIs are not yet widely used commercially. Yet TUIs provide physical interfaces that have greater potential to reduce cognitive load and offer an intuitive interaction to support activities such as learning, problem solving, and design.

2.3.1 DESIGNING INTERPLAY OF VIRTUAL AND PHYSICAL

TUIs can be considered a specific implementation of the original notion of ubiquitous computing, which aimed at allowing users to remain situated in the real world, while retaining the primacy of the physical world (Shaer and Hornecker, 2010; Wellner et al., 1993; Leigh et al., 2015). Since TUIs provide physical objects in order to interact with the virtual environment, they rely on metaphors that give physical form to digital information. The TUI designer determines which information is best represented digitally and which is best represented physically (Shaer and Jacob, 2009; Bakker et al., 2012; Want et al., 1999). Tangible Models is good example, because this platform uses augmented reality where digital images are superimposed on tangible blocks blending reality with virtuality. The ARToolKit is used to rapidly develop augmented reality applications. Spatially manipulated tangible blocks sit and operate on a large horizontal display. When designers manipulate multiple blocks, each block allows direct control of a virtual object by communicating digital information visually to the user. Through manipulating 3D tangible blocks, the designers also gain tactile feedback from their interaction (Abdelmohsen and Do, 2007; Anderson et al., 2000). TUI developers consider design issues such as physical syntax (Ullmer, 2002), dual feed-back loop (digital and physical), perceived coupling (the extent to which the link between user action and systems response is clear) (Hornecker and Buur, 2006), and observability (the extent to which the physical state of the system indicates its internal state) to make physical interaction devices understandable (Shaer and Jacob, 2009). It is a challenge to develop frameworks to provide the vocabulary for developing TUIs that link the virtual and physical. Therefore, the discussion, comparison, and refinement of designs with respect to these issues is often performed in an ad-hoc way that does not facilitate generalization (Shaer and Jacob, 2009).

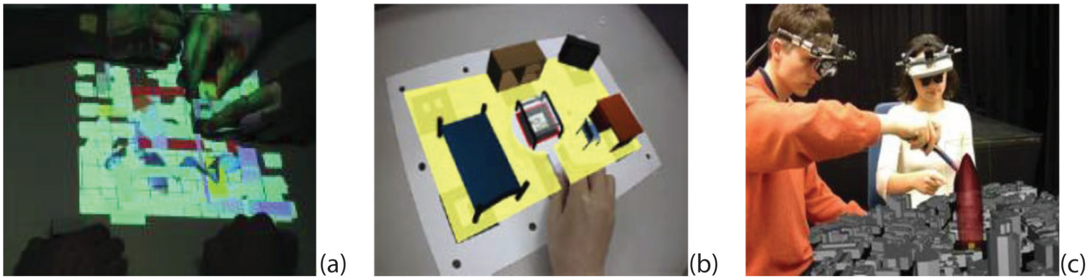

Figure 2.4: (a) BUILD-IT bricks. Used with permission (Fjeld et al., 1997); (b) Interior Design application paddle. Used with permission (Kato et al., 2001); (c) ARTHUR wand. Used with permission (Nielsen et al., 2003).

1) Tangible Keyboard

The Tangible Keyboard design addresses these considerations in the following ways: The physical syntax is that of a Sifteo Cube expressed as a rectangular disc with a display. The affordances of these devices include grasping, neighboring, tilting, and pressing. The application provides feedback from the physical interaction through changes in the visual display on the cube as well as on the tablet. Audio and haptic feedback also confirms a digital response to a physical action. In this design, based on the Sifteo cubes™ platform, the interplay between the physical and the digital is visual, tactile, haptic, and audible.

2) Tangible Models

The Tangible Models design addresses the interplay of physical and digital through visual feedback only; since the physical location is sensed via a camera, the feedback from the system is entirely visual. The movement of a physical device is seen on the display as the camera displays the movement. The emergence of a 3D model from a physical block device is achieved by sensing the marker on the physical device and superimposing the 3D model on the location of the marker. In this system, based on the ARToolkit, the interplay between the physical and digital is tactile and visual.

2.3.2 SELECTING FROM MULTIPLE GESTURES AND ACTIONS

A TUI designer needs to define an interaction model comprising a user action–system response pair for each possible context of use. In the physical world, there are numerous actions that can be performed with any physical object (Shaer and Jacob, 2009). The interaction model for TUI defines which actions are meaningful in which context. The designer needs to develop this interaction model, effectively communicate it to users, and then implement a solution for computa-