Knowledge of Today for the Design of Tomorrow

Masitah Ghazali, Alan Dix
Computing Department, Infolab21, Lancaster University, Lancaster LA1 4WA, England
{masitah, dixa}@comp.lancs.ac.uk

The vision of ubiquitous and tangible computing is a world filled with a plethora of objects beneath which lie vast amounts of computational power. This poses new design challenges in the attempt to bridge the physical and digital worlds. This paper describes a study of mundane electronic devices in order to understand what makes physical interactions and physical-logical mappings natural and comprehensible. We are looking particularly at how these principles exploit our innate human understanding of the physical world to allow fluid, natural interaction. Our aim is to exploit the design knowledge and experience embodied in these existing devices in order to re-apply it to novel device design. An initial collection of interaction principles is presented, which offers a new way to understand natural interaction with tangible controls. We hope the findings will enable us designing a richer engaging experience with novel devices.

Tangible user interface, ubiquitous computing, consumer appliances, physical interaction, fluidity, affordances.

1. INTRODUCTION

Every day we interact with physical artefacts. Devices and consumer appliances are used in order for us to get our job done in our daily activities. Sometimes, we have trouble understanding how to manipulate these devices and appliances. We need to read the manual before we can actually use them. But other devices and appliances have been designed in a way that enables the user to interact naturally. This naturalness is what we would like both from these mundane devices and also from novel devices.

In this paper, we study real physical controls on really-used artefacts in order to understand the features of physical interaction and of the physical-logical mapping that make them comprehensible and natural. Our aim is to use rich knowledge implicit in the design of day-to-day artefacts to uncover principles that can be used in the design of novel tangible interfaces.

This naturalness of physical interaction is related to both Gibson's notion of natural affordance [12], as well as the more culturally informed aspects of affordance brought into HCI by Norman [17] and Gaver [10], Dix et al. [6a] describes this naturalness of interaction as fluidity, which is "the extent to which the physical structure and manipulation of the device, naturally, relate to the logical functions it supports". This paper expands on this notion of fluidity.

Many of the studies of day-to-day artefacts in HCI, notably much of Norman's work (e.g. [17]), focus primarily on the failings of design and the way appropriate use of cognitive or other design principles might have avoided these design mistakes. The lesson from these is mostly about what to avoid! In contrast, we are looking particularly for the positive lessons from day-to-day devices, in particular how the tangible nature of these can harness innate human abilities.

We begin this paper with a rationale as to why we believe it is productive to study mundane devices and appliances when our eventual aim is to understand the design of novel tangible and ubiquitous devices. We will then look at related work set within a model of physical-logical interaction. Day-to-day devices, traditional GUI interfaces, augmented reality and tangible interfaces all draw on innate human understanding of physical interaction, and so we will look at some of the properties of 'real world' interaction with physical objects.

2. MOTIVATION

Why do we consider day-to-day devices at all? These are typically independent devices with low computational power and very traditional technologies. In contrast research in tangible and ubiquitous technologies seems to be technologically far removed. This radical view of the future has captured the media's imagination, for example ubicomp researchers contributed strongly to the film *Minority Report* [22] which has popularized the ubiquitous vision of the future first articulated by Weiser [24]. This science fiction world seems far removed from the devices we see today, but perhaps they are not so different after all.

1.1 The Vision

Ubiquitous computing paints a world where the day-to-day activities of our lives are suffused with computation. Each item from briefcase to breakfast-cereal packet becomes a locus for interaction. Some of this is incidental to the activities we are doing [6b]: the briefcase keeps track of its contents and talks to the wall calendar so that it can warn if an important document for today's meeting is missing. But other actions require more intentional although still implicit interactions [20]: tipping the breakfast place-mat from side to side to turn the pages of the morning paper displayed on it. Others are more explicit still, the magic wand that acts as universal control [9].

We are focusing in this paper on the latter two categories: the intentional but implicit and the more explicit interactions. Both involve physical objects or controls. However, as the world fills with physical objects that have meaning in the electronic world, then how do we understand those meanings? How do we turn the device that is a wonderful demonstration when you know how it works into an object that is "pick up and use"? And even when you know how it works, what are the affordances of the object and the properties of the physical–logical relationship that allow the use to become natural?

1.2 The Mundane

In the *current* world our lives are suffused with computation. Many items from Walkman to washing machine are a locus for interaction. Some of this is incidental to the activities we are doing: the set-top box that monitors your watching habits and consults the electronic TV guide so that it can pre-record the programmes you may want to see later. But other actions require more intentional although still implicit interactions: the volume control on the phone that naturally sits under your thumb. Others are more explicit still: the dial and switches on the washing machine control panel.

Focusing again on the latter two categories, designers of day-to-day products are constantly faced with the issue of how to make these devices comprehensible to ordinary people. A MiniDisc controller that makes a wonderful demo to a group of fellow designers, or even computer scientists, could win you a design award, but will be a market flop if people cannot pick it up and use it. A 27 page manual is not acceptable whilst jogging.

1.3 Harvesting the Experience in the Ordinary

So, we can see that the novel interactions envisaged in ubiquitous computing, although different in detail, do share much with more mundane day-to-day appliances. By studying these appliances we can learn much that would be hard or impossible to learn by extensive experimentation with novel devices.

First we all have an extensive first and second hand knowledge of these devices and their use. Of course we have to be careful as researchers and designers when generalizing from our own anecdotal experiences; however, neither should we ignore this rich resource.

Second these devices are only popular if they 'work' for people. Although little-used controls may not be optimal it will generally be the case that the more heavily-used aspects will have designs that have been found to be usable otherwise the products would not sell. Obviously this second argument does not hold where there is an effective monopoly, as is the case with certain software goods, but for most consumer appliances there is considerable competition and also consumers will have seen them in friends' houses, or for personal products perhaps borrowed them and tried them out.

Finally these products embody the knowledge of their designers. Some are successful because they happen to be, but many are successful because they are designed to be. Because of the different styles of the disciplines, much of this design knowledge is communicated through exemplars rather than abstracted principles. However, this community knowledge, as well as individual skills, are evidenced in the products we find.

Of course not all appliances are well designed; in particular, aesthetics may dominate usability. Indeed, the failings of such devices are the constant topic of after-dinner conversation in HCI conferences and are often lampooned in books and publications (e.g. [17]). However, this should not detract from the overall ease with which we conduct most of our technological use of artefacts.

3. RELATED WORK

Interfaces to consumer products are also studied closely in an industrial design setting. Overbeeke et al. [19], discuss 10 rules (guidelines) focused particularly on making engaging products, for example “don’t think beauty in appearance think beauty in interaction”. Whilst our aim has been more to understand the visceral qualities of mundane interaction, their more aesthetic and our more articulatory approaches have common features. For example, the quoted rule, which they relate to Dunne’s “aesthetics of use” [8], concerns the naturalness of physical interaction. In addition, they take as a starting point the observation that modern devices often hide their functionality behind buttons and icons, and propose designs that expose functionality, echoing the issues of exposed state and compliant interaction we will discuss.

Our work also complements other work in tangible interfaces and augmented reality, for example, Ullmer and Ishii's MCRpd interaction model [23], Benford et al.’s sensible/ sensable/ desirable (SSD) framework [1] and Koleva et al.’s tangible user interface framework [15]. Each of these considers aspects of the relationship between the physical and digital

Looking at the conventional interface literature, it is interesting to consider Shneiderman's direct manipulation principles: continuous representation, physical actions instead of syntax and rapid incremental and reversible operations [21], and also other early work on understanding direct manipulation [16]. These, and indeed the whole GUI endeavour, are effectively about trying to harness the naturalness of physical interactions in the digital domain.

We can see the connections between these related areas if we consider a simple 2x2 matrix looking at the controlling devices and the functionality controlled; both of which may be physical or virtual. Of course no device is completely virtual, some physical interaction with the user is always necessary, with the possible exception of direct brain sensing! By virtual, we mean devices such as on-screen buttons, which have no direct tangible properties.

		Functionality (logical state)	
		Physical	Virtual
Devices	Physical	the real world, exposed mechanisms	tangibles, consumer devices, augmented reality
	Virtual	industrial control, heads-up displays	GUI and direct manipulation

TABLE 1: styles of physical–virtual interaction

In the real world we have physical devices with an immediate physical effect (the thing itself!), in direct manipulation and graphical user interfaces we have logical devices and logical effects, and in our studies, tangible and some ubiquitous computing we have physical devices with logical effects. All exploit our innate abilities to live and act in the physical world.

In the bottom left corner of Table 1 we have placed industrial ‘glass’ controllers and similar kinds of controls such as heads-up controls in an aircraft cockpit. These are effectively some form of virtual control of a physical process (the operation of the factory, or movement of the plane).

When looking at a simple physical object, such as a cup, there is no separate logical state and our interaction is guided by simple affordances [18]. For a more complex, mediated interface the effect on the logical state becomes critical: the speaker dial affords turning but at another level affords changing the volume. Hartson [13] introduces a rich vocabulary of different kinds of affordances to deal with some of these mediated interactions. Benford et al.’s SSD framework [1] uses potential mismatches between physical and logical states as a design opportunity; analysing the sensable aspects of the physical device (what the system can sense), the sensible actions the user might reasonably do to the device, and the potential desirable additional functions.

Finally the start point of our work is the concept of fluidity introduced in Dix et al. [6a], which emphasises the importance of the physical properties of the device. Whereas the SSD framework is primarily concerned with what it is *possible* to achieve, fluidity is focused on what is *natural* to achieve.

4. UNDERSTANDING PHYSICAL INTERACTION

As we have noted, direct manipulation, augmented reality and tangible interfaces all emulate or use interaction with real physical objects. The reason these different techniques work so well is that we have deep-seated mental and physical abilities attuned to the physical world. There is strong evidence that we reason differently with different kinds of experience, for example, physical vs. social situations [2, 3, 7]. Whilst we can reason explicitly about most types of situation this is both slower than more innately driven responses and requires conscious attention. This is why the 'M' (mental processing) operator in Card, Moran and Newell's keystroke-level model was always so problematic [4]. Interfaces that break the natural properties of physical interaction may be difficult to learn, difficult to use or lead to various kinds of superstitious interpretative models [6b].

Furthermore, at the lowest level, motor activities involve neurological feedback loops within our bodies that do not involve conscious thought at all. These loops operate in time scales far faster than can be controlled using more cognitive processes and are hard to train, for example, learning new fingering patterns for a musical instrument or physical actions during sports. Low-level hand-eye coordination, such as those used in Fitts' Law tasks, are also largely unconscious. Where systems emulate aspects of the physical world they can take advantage of existing low-level responses rather than requiring new ones.

It is often hard to distinguish those aspects of devices that work because of cultural norms developed due to exposure to technology, which can thus be expected to change (albeit slowly) over time, as opposed to more innate understandings of the physical world. Whilst it is not essential for many purposes to separate these we can try to make this distinction based on the properties of natural physical objects such as stones. These properties (often violated by electronic and even mechanical devices) include:

Directness of effect – A small push makes a small movement, a large push makes a large movement; a push in one direction followed by an equal push in the opposite direction gets something approximately back where it started.
Locality of effect – When you do something it has an effect here and now. If you push a stone you do not expect it to move 5 seconds later.
Visibility of state – The fixed appearance, shape and other properties may be very rich, but the changeable ones are relatively simple (location, orientation, velocity) and immediately visible.

If a physical object is constructed to violate these properties, for example, a beach ball part-filled with water, the behaviour appears 'magic' or 'alive' as the ball appears to move of its own volition. Part of the complexity of computer systems is that they violate these simple principles of physicality.

5. MUNDANE DEVICE SUCCESS

In order to understand how these natural interactions can be used effectively in design, we have studied a selection of day-to-day devices and consumer appliances including a washing machine and speaker volume control. We have sought to analyse and represent some of the rich physical interactions available on these mundane appliances.

In most of these, the explicit design of the physical object enables the user to understand how to manipulate the device as they exhibit strong affordances. However, we see that there are additional aspects of these devices that exploit the physical form of the device to inform the users' interaction with the logical function they control. In some cases we will see that this is not the case and then the devices employ various 'recovery' strategies to make the non-physical aspects more obvious.

One of the techniques we have used is to represent separately the states of the device and of the underlying logical state (the left and right hand sides of figure 1). For each we have produced a simple state transition network and then examined the relationship between the two. However, for certain types of physical interaction we have had to extend normal state transition notation to deal with 'bounce-back' controls.

5.1 Exposed State

Look at a simple light switch. Even if the light itself is not working the switch clearly has two states. That is the physicality of the device exposes some aspects of state. We may not know to what the switch is connected (light or air conditioning) or whether up means off or on, but still there is very visibly two states. To take this to the extreme, imagine physically pulling the switch off the wall, even with its wires torn out the device has physical states.

This exposed physical state of the device is often used to create very natural interactions by directly mapping the physical device states to logical states. For example, figure 1 shows the one-to-one mapping between the state of a switch and the state of the kettle it controls.

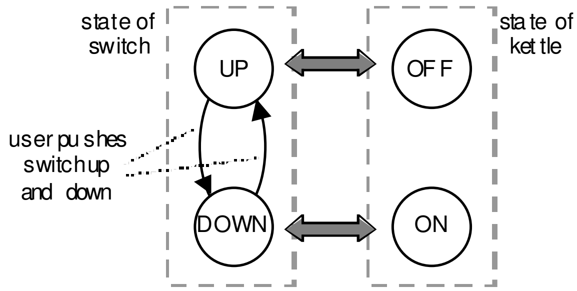

FIGURE 1: States for simple switch

As noted above, there is a separate issue as to whether the user knows this mapping (is up off or on?) or how the user gets to know the mapping (affordances, labels?). However, note that the user can make a reasonable guess that it is a two-state thing being controlled, and because of the simple relationship between physical device state and logical controlled-system state the user is in a good position to infer the mapping with use. This ability of the user to manage without necessarily knowing mappings ahead of time is typical of physically natural interactions.

The washing machine dial is a more complex example of exposed state. The dial shows the chosen program (indicated by written legends) and when a wash is in progress it also shows the current state of the wash cycle. This device displays the internal washer state as well allowing the user to set it (see section 5.5).

Obviously, the visible state of a control can only be used when there are a corresponding number of internal states although this can be quite large, for example the washing machine dial shows a large number of programs and wash states.

In contrast to exposed state, there are controls where the physical appearance does not indicate any obvious state. An example is the twist control of the speaker in figure 2, which has no intrinsic on/off position given by its physical shape. The user cannot tell from the dial itself the level of the sound. To some extent this is unnecessary – you can hear the volume, but without an indicator of the current setting it is hard to see where in the range it is – can you make it twice as loud, ten times as loud? Often additional labels (as in the washing machine) are used to expose the rotational state of dials like this, for example, a single dot to give a point of reference.

Sometimes hidden state is the result of aesthetic rather than usability decisions, but also hidden state controls can be useful where the logical system has large numbers of states, or where the calibration between device state and logical state needs to be dynamic. For example, if the dial could turn completely round several times to increase or reduce volume there would be no one-to-one relationship between location and volume. Also if the same control is used to manipulate different aspects of the logical state in different modes or there are large numbers of internal states, then it may be impossible to have a simple mapping.

FIGURE 2: Speaker control

Hidden state can be exposed in two ways, pre-use and while-using. Pre-use exposure is when additional features like text, signs, pictures, and lights that can be found around or close to physical controls give suggestions or instructions to the user of how to manipulate the device control. The marks are pre-use in the sense that before actually manipulating the device the user can begin to build a mental model of the hidden physical–logical mapping (c.f. [17]). Pre-use exposure is similar to the notion of *feedforward* in Wensveen et al.'s Interaction Frogger [25].

While-use exposure occurs when the act of manipulating the device makes the state or changes in the state perceived through haptic, aural or other feedback. We will return to this later when we discuss tangible transitions.

In older devices the physical control was often connected directly to the internal mechanism. As controls have become electronic this connection is often lost and this becomes apparent in hidden state. For example, old tape recorders have buttons that stay depressed while the corresponding activity is occurring (play, record, etc.) – strong exposed state; in contrast, electronic 'touch' controls initiate the change of state but have no apparent state themselves. Mechanical push buttons have at least some intrinsic haptic feedback that the press has occurred whereas capacitative or low-travel buttons may have no physical feedback whatsoever. In such cases one sees the sure sign of poor exposed state – an additional on/off light or other soft visual display.

5.2 Tangible Transitions

Some physical controls provide the naturalness of interaction by embedding a sense of feltness when manipulating the controls. This may augment exposed state or in the case of hidden state provide while-use exposure. In the example of the speaker control, the physical control has a palpable bump so that the user can feel it go past the on/off position. This does not give the user knowledge of the current state before grasping the control, but whilst manipulating the device, the user is made aware of critical transitions.

The latter effect has been emulated in the iDrive haptic controller for the BMW series 7 [14]. The controller itself is a small knob with no specific markings and is used to control a variety of functions through a menu interface. Electronic haptic feedback means that as the user twists the knob to move through menu options a small bump is felt for each menu transition. This can allow the user to perform frequent selections without needing to look continuously at the screen – very important whilst driving.

5.3 Bounce Back

Some control devices return to their initial position soon after we release our fingers or hands from the knobs/buttons. For example, the on/off power button on many PCs. When we push the button in, the effect of this action starts up the system and the button returns to its initial position. This particular effect is what we call 'bounce back'. Other examples that exploit bounce back include joysticks, mouse buttons, a mobile phone's volume controller and MiniDisc controls.

FIGURE 3: On/Off control with bounce back – is it on or off now?

The bounce back control in figure 4 has aspects of both exposed and hidden states. It is exposed in that it is clearly 'in' or 'out'. However, the 'in' state is a *transient state*, it only stays in the state while a finger is actually pressing it. As soon as the pressure is released it bounces back to the 'out' state and so there is only a single stable exposed state. This lack of a meaningful exposed state means that bounce-back buttons typically rely on a screen display or some other sort of indication to show the present state the system is currently in after the physical manipulation has taken place.

One reason for this hidden state is that some PCs allow you to turn on the machine using the power button, but only have a 'soft' off invoked by software to ensure that data is properly saved. In this case the user would control the off-to-on transition, but the system would control the on-to-off transition. In fact, the photographed system does not behave like this; it appears to be an unnecessary case of hidden state with a characteristic power light near the button to expose the hidden state. The real reason for the bounce back seems to be aesthetic; a two state on–off switch would not look pretty on the front of the PC case.

5.4 Inverse Actions

We return now to the speaker volume dial (figure 2). As with most dials, turning the rotary knob clockwise increases volume, turning it anti-clockwise decreases volume. This exploits natural physical inverse actions – if you push a cup across the table you can also push it back in the opposite direction; unless it falls off the edge, opposite pressures have opposite effects.

FIGURE 4: Volume control – linked buttons.

As in GUI, the inverse action acts as an 'undo' and so reduces the risk of exploration [5]. However with physical devices it is not just that an inverse exists but that the inverse exploits a natural physical inverse such as push/pull, twist clockwise/anti-clockwise, or push up/down. In the best cases this is intrinsic to the device (as in the speaker's rotary knob), but may also be made apparent using visual or tactile decoration. Figure 4 gives an example of the latter where two buttons are clearly linked by being 'yoked' together.

Inverse action is especially important if the user does not have a perfect knowledge of the physical–logical mapping; the user can experiment with the physical control but recover effortlessly if things go wrong. A particular case of this is when a physical control may manipulate more than one logical function. For example, some mobile phones have a small 'scroll' button that can be pressed up or downwards. This may control volume whilst in the middle of a call or scroll through lists when searching the address book. Although this sounds very confusing it does not prove to be in practice. There is an immediate visual or audible feedback of the effect of the control and if the effect is not as desired the natural inverse makes it easy to correct.

Inverse actions, in some other cases, work together with exposed state to deliver natural interaction, for example, the tuning knob on old radios used to mechanically move an indicator on the 'display'.

The naturalness of inverse actions' interaction may only be achieved when the user gets immediate feedback – for instance, the sound of the speaker increasing and decreasing. However, feedback is sometimes delayed, for example in an electric cooker the time it takes to heat the metal in the cooker's rings. As we discussed, temporal locality is one of the features of physical interaction, and not surprisingly these delays are not dealt with naturally. For example, many people will adjust central heating beyond the desired temperature to 'heat the room more quickly'.

5.5 Compliant Interaction

The rotary knob on the washing machine (see figure 5) is not just a good example of exposed state, but also exhibits symmetry of interaction. The user sets the program by turning the dial, but the system also turns the dial itself as the program advances.

Exposed state and compliant interaction differ in that compliant interaction has some kind of mechanical movement that changes the control in the same way as the user would interact. A simpler example is the on/off switch on some electric kettles. This can be moved up and down by hand, but when the kettle boils flicks to the off position. Old tape recorders also did this and the 'play' button would bounce back up when the tape reached the end.

Note how the kettle's on/off switch differs from a simple on/off switch such as a light switch. In the latter there is no control involved from the system, it solely depends on the user's interaction.

FIGURE 5: Washing machine and its control.

Compliant interaction means that the user can easily learn the relationship between the state of the control and the state of the device. The naturalness of compliant interaction enables expert users to use the device to exert fine control over the system's action. This is evident in expert washing machine users who can intervene in the washing program, such as skipping parts of the program, and start in unconventional places, as they learn how to fine-tune the device.

In principle this control could give rise to confusion as turning the dial does not complete the wash cycle that the system has been programmed to do. In practice this does not seem to occur with washing machine use or the electric kettle (switching it off is not assumed to have magically boiled the kettle). However, this does appear to be a potential danger for less well-understood applications.

6. CONCLUSIONS

In this paper we have explored the way that the design features of current day-to-day appliances can be used to inform next generation interfaces. We have focused on the aspects of the physical controls that correspond to natural physical interactions in the world. Studying these day-to-day devices has led to a number of principles and issues of physical interaction.

Although some of the principles are generally 'good' ones: exposed state, inverse action, compliant interaction; there are circumstances where they are and should be broken. For example, if there are many states or a variable mapping then exposed state is not possible.

The adequacy of interaction is normally seen in the light of a complete system; however, we have focused on the physical devices used for interaction with the system. Clearly rich interactions require high-level cognitive understanding, but, if the finer aspects of interaction recruit low-level abilities through the physicality of devices, then our higher-level abilities are freed to focus on the real purpose.

Our investigative approach has combined what can be thought of as an epidemiological study of devices that are extant, more psychological analysis of device use, common knowledge about good and bad design and detailed formal analysis. Most of the devices we have studied exhibit several 'good' and 'bad' properties and the effectiveness is a combination of designed and accidental properties of the device combined with skilled human behaviours arising from cultural, learnt and innate causes. To attempt to disentangle completely all these issues would not be productive for design purposes and our multi-paradigm approach has allowed a broad analysis. However, attempting to obtain some purchase on the complex interactions and trade-offs of physical design does lead not only to insight but also potential directions for more detailed experimental studies of individual effects.

In summary, this study offers new ways to understand natural interaction with tangible controls. We believe that this will allow the experience embodied in existing mundane appliances to be applied to the design of novel ubiquitous devices. We have already used these principles in studying novel devices [11] and we intend to continue to explore these issues and hope that this paper will also inspire others to look more closely at the everyday world around them to inform and inspire the effective design of novel interaction.

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