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ORIGINAL ARTICLE

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A taxonomy for and analysis of tangible interfaces

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Abstract There have been many research efforts devoted to tangible user interfaces (TUIs), but it has proven difficult to create a definition or taxonomy that allows us to compare and contrast disparate research efforts, integrate TUIs with conventional interfaces, or suggest design principles for future efforts. To address this problem, we present a taxonomy, which uses *metaphor* and *embodiment* as its two axes. This 2D space treats tangibility as a spectrum rather than a binary quantity. The further from the origin, the more "tangible" a system is. We show that this spectrum-based taxonomy offers multiple advantages. It unifies previous categorizations and definitions, integrates the notion of "calm computing," reveals a previously un-noticed trend in the field, and suggests design principles appropriate for different areas of the spectrum.

1 Introduction

At CHI 1997, Ishii and Ullmer [28] presented "tangible user interfaces" (TUIs), which they defined as user interfaces that "augment the real physical world by coupling digital information to everyday physical objects and environments." This paper, building on others of a similar spirit [18, 26, 46], aroused great interest in the research community—"CiteSeer" has 190 citations for the TUI paper alone [12].

While the terminology has varied from paper to paper (e.g., "passive real-world props" [26], "graspable" [18], "manipulative" [25], or "embodied" [16]), these multiple terms are largely distinctions without a difference, and owe more to the history of an evolving field than to the nature of the work. As Ullmer and Ishii [65] later suggest, we adopt the most common phrase, "tangible," to refer to them collectively. They all share the same basic paradigm—a user uses their hands to manipulate some physical object(s) via physical gestures; a computer system detects this, alters its state, and gives feedback accordingly.

This basic paradigm has now been well demonstrated, and a few attempts at defining and/or organizing parts of the space have been made, but the field has not been able to rigorously proceed far beyond "proof of concept" examples. TUIs have been largely an "I know one when I see one" field—can we move beyond this? Now that the design space has been repeatedly sampled, we attempt here to build on these earlier organizational attempts. Our goal is to provide a useful and general framework for defining the space, for comparing works in the space, for helping guide the design of such works, and to generalize and unify the preceding frameworks.

We begin, therefore, by defining the space. Given this definition, we then present our taxonomy for the space. We then motivate the taxonomy by discussing its properties. We close by discussing future directions.

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2 Defining TUIs

What, then, are TUIs? In their original paper, Ishii and Ullmer [28] define them as user interfaces that "augment the real physical world by coupling digital information to everyday physical objects and environments." In their later work [65], they give a narrower definition, defining them as one that, in addition to other restrictions, eliminates the distinction between input device and output device, although "interesting interaction regimes are highlighted by relaxing these expectations." In this paper, we perform that relaxation, and seek to obtain that interest.

We begin by casting our TUI net very broadly, even more broadly than the first definition above, and then show how it can be narrowed in interesting ways. We therefore begin with an extremely broad script that characterizes TUIs:

1. Some *input event* occurs. This input event is typically a physical manipulation performed by a user with their hands on some "everyday physical object," such as tilting, shaking, squeezing, pushing, or, most often, moving. Later, we will remove the "typically" qualifier.
2. A computer system *senses* this input event, and alters its state.
3. The system provides feedback. This *output event* is via a change in the physical nature of some object—it alters its display surface, grows, shrinks, makes a sound, gives haptic feedback, etc.

To demonstrate this sequence, and to illustrate the great variety of systems that have been termed as TUIs, we show four examples:

1. The "Great Dome" [28]. Users employ physical objects, for example, a small model of the MIT "Great Dome" campus building. The system detects two motions (rotation and translation) of the device atop a workspace displaying a campus map. The system correspondingly rotates and/or translates the view of the map displayed on the workspace. The input events are rotation and translation. The output event is to alter the display of the underlying workspace. Two objects are used; one for input which is indicative of a building, the other for output is an augmented desktop.
2. The "Sketchpad" [35]. Users have a small key chain computer with a display. By shaking the computer, the entire display is cleared. The input event is a shake; the output event is to clear the screen. One "non-everyday" object is used for both input and output.
3. The "ToonTown" [57] system. There is a "virtual auditorium" with small figures representing users of a chat system. By moving the figures about in the auditorium, the audio levels of the users are adjusted. Here, the input event is translation; the output event is in audio changes. Two objects are used, both of which are representative of, but not equal to, "real-world" objects.
4. The "photo cube" [68]. A photo cube has six RFID tags on it, one for each face of the cube. When a face of is brought to an augmented tablet computer, the Web home page of the person whose picture is on that face is displayed on the tablet computer. The input event is a spatial motion, where the orientation of the cube is significant. The output event is to alter a display. One everyday object is used for input, a non-everyday object for output.

These four examples help illustrate the great variety of the space; if we listed four more examples, we could have four equally disparate point samples. How can we take this great diversity of systems and meaningfully reason about them and design within their space?

3 A taxonomy for analysis

As mentioned above, the preceding script is very broad. In fact, it's so broad that it doesn't lend us any focus or clarity of analysis. However, we found narrowing the TUI definition problematic. For example, consider the many "digital desk"-type systems [71], in which users move everyday physical objects around a desktop, and cameras detect that motion and adjust a computer system accordingly. These are not typically considered a TUI, but why not? There are systems, which define themselves as TUIs, including the seminal Ishii–Ullmer paper (e.g., [28, 66, 67]), which use exactly this same configuration. And what of existing interfaces employed in industrial design? Are car-seat controls that look like car seats TUIs? Greeting cards that play an audio file when opened? Joysticks shaped like steering wheels? Joysticks that are *not* shaped like a steering wheel? Computer keyboards? We have found no useful *binary* characteristic function that meaningfully includes some of these, while excluding others. Instead, we find it useful to view "tangibility" as a multi-valued attribute.

How many values should be chosen? How many dimensions in the taxonomy? The more dimensions the greater the descriptive power, but the greater the overhead, the lesser the simplicity and clarity. We propose here, and justify later, that a 2D taxonomy is fruitful, one that uses as its dimensions *embodiment* and *metaphor*. The higher the levels of these attributes in a system, the more tangible it is. This is not to say that it is "better" or "worse," simply that it is more "tangible," and that there are design trade-offs associated with that placement. We now show the characteristics and their levels with examples from both traditional HCI and TUIs.

3.1 Embodiment

In the first step of the script, users are attending to some object while they manipulate it. In the last step, they are being informed of the result. How closely tied is the input focus to the output focus? To what extent does the user think of the states of the system as being "inside" the object they are manipulating? To what extent does the user think of the state of computation as being *embodied* within a particular physical housing? Building on prior work [16], we propose this characteristic of *embodiment* as one of the two axes of our taxonomy[1]. We present four levels of this characteristic:

[1] This is not to be confused with the "embodied interaction" of Dourish [14], which denotes "the way that physical and social phenomena unfold in real time and real space as a part of the world in which we are situated." As Dourish [14] points out, that sense of "embodiment" incorporates all of TUIs as a small subset. Here, we refer to a much narrower sense.

Full In the limit case, the output device *is* the input device: the state of the device is fully embodied in the device. This is analogous to clay sculpting: one pushes on the clay and views the result on that same clay. This interaction is the most common type we see when we interact with the physical world—things receive some physical manipulation, and change accordingly. Some TUI examples are the "TiltScreen" [46] and "Gummi" [55] systems, where, as the user tilts (TiltScreen) or bends (Gummi) a PDA, the display alters. Conceptually, the entire state of the device is embodied within the system. More playful examples are the "Platypus Amoeba" [11] and "Trible" [36], where a reactive soft-skinned sculpture responds to touching and petting by changing lights on its surface, vibrating itself, etc. The "Sketchpad" system [35] mentioned above is another example.

Nearby In this case, the output takes place *near* the input object, typically, directly proximate to it. The output is tightly coupled to the focus of the input. In HCI, this step was first demonstrated by input devices like the light pen, which altered the display directly beneath them. There are many examples of this level of embodiment in TUIs. For example in the "Bricks" [18] and "I/O Brush" [52] systems, the user moves physical bricks/brushes about an augmented tabletop, controlling the display on that tabletop. The "Great Dome" [28] and "photo cube" [68] systems mentioned above are additional examples.

Environmental In this case, the output is "around" the user, typically in audio though others are possible (e.g., adjusting ambient light or heat levels). This is termed "non-graspable" by Ullmer and Ishii [65]. There is a tenuous link between the input object and the output, but the output is viewed as, somehow, apart from it. In conventional HCI, this is equivalent to a sound-editing application. There are many examples of this level in TUIs, for example, in the "ToonTown" system [57] mentioned above, the user translates physical avatars representing users of a chat system, and the audio from that user is adjusted accordingly.

Distant In this case, the output is "over there," on another screen, or even another room. In conventional HCI, this is equivalent to a TV remote control, in which visual attention is switched between the input (the control) and the output (the TV screen). There are many examples of this level in TUIs, for example, in the "Doll's Head" [26] system, the user's input focus is on a doll's head and a translucent piece of glass for input, and users look over to a nearby screen to observe the result of their actions.

Figure 1 summarizes these levels, showing images from systems mentioned above.

Applications may span various levels. For example, the Platypus Amoeba just referenced makes sounds ("environmental" embodiment) in addition to changing lights on its surface ("full"). The "PingPongPlus" system [29] detects when and where a Ping-Pong ball strikes a table and employs both "environmental" and "nearby" levels of embodiment.

As embodiment increases, the "cognitive distance" between the input mechanism and the result of that mechanism decreases. This has trade-offs. If one is designing a system in which it is important that the input and output object(s) be cognitively dissimilar, then an embodiment of "nearby" or even "distant" may be most appropriate, depending on the nature of the task. For systems where the designer wishes the user to think of the system as "living" in a single place, conversely, an embodiment of "full" will be most powerful.

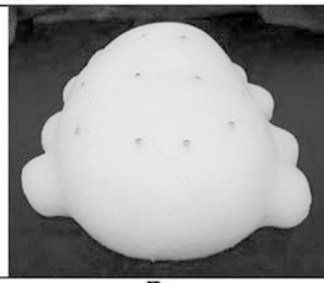
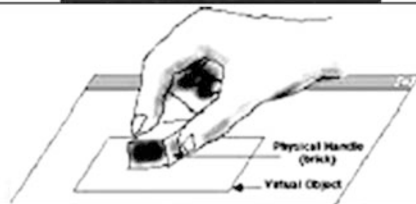
3.2 Metaphor

3.2.1 The importance of metaphor

Metaphor is widely recognized as an enormously powerful ingredient in thought and design. Cognitive anthropologists argue that the ability to use metaphor is the defining characteristic that separates the minds of early humans from modern humans [40]; philosophers of science believe that metaphor lies at the heart of how our theories of the world are created, explained, and communicated [8, 32]. By aligning our axis with this known powerful and well studied concept, we can apply all those studies, and rules of design and principle, to TUIs. We believe that metaphor is particularly appropriate for TUIs, as opposed to other interfaces, due precisely to their physical tangibility. Once parts of an interface are made physically tangible, a whole realm of physically afforded metaphors becomes available. A designer can use the shape, the size, the color, the weight, the smell, and the texture of the object to invoke any number of metaphorical links. Mithen [40] argues that "the most powerful [metaphors] are those which cross domain boundaries, such as by associating a living entity with something that is inert or an idea with something that is tangible." Tangible interfaces, which can have exactly these properties, therefore, have this potential.

We, accordingly, chose metaphor as one of the axes of our taxonomy. In a TUI sense, this means: is the system effect of a user action analogous to the real-world effect of similar actions? This has been termed the "physical effects principle" [16] or "sympathy" [31]; we prefer the more familiar and powerful term, "metaphor." To quantify the amount of metaphor, we roughly group metaphor into two types: those which appeal to the *shape* of an object, which we term "metaphor of noun," and those which appeal to the *motion* of an object, which we term "metaphor of verb." The more that either type of metaphor is used, the higher the interface on our scale. We base this grouping on results from cognitive psychology [20, 21], which show that noun and verb are deeply natural and intuitive concepts,

Fig. 1 The levels of embodiment, with examples

Embodiment	Example	Picture
Full	Amoeba	
Nearby	Bricks	
Environment	ToonTown	
Distant	Doll's Head	

arising even in deaf–mute children who are taught no linguistic grammatical structure. This grouping, then, gives us four rough levels, with gradations at each level:

1. None Sometimes, there is no metaphor employed at all. In conventional HCI, this level of metaphor is that of a command-line interface, where the typing gesture has no correlation to the effect—the analogies are at higher, conceptual levels. Some TUI examples of this are the "Bit Ball" [50] and "Beads" [50] systems. In the first, squeezing a ball alters audio—in the second, connecting two beads alters their visual appearance. In each of these cases, users employ various physical manipulations to control the system, but these manipulations are deliberately not connected to any real-world analogy.

2A. Noun In some systems, an analogy is made to the physical shape/look/sound of object(s) in the system—"an <X> in our system is like an <X> in the real world." However, the actions employed on/with that object are either not analogous or only weakly so. In conventional HCI, this was the level reached by the original "Windows/desktop" systems (such as the "curses" package), where virtual windows on virtual desktops were analogous to physical pieces of paper on physical desktops. However, most of the physical operations on real desks and paper (clean, crumple, burn, stack, staple) have no virtual analogy, and many of the virtual operations have no physical analogy (iconify, resize). The analogy is primarily a spatial one. In the TUI realm, this level is reached by systems in which the look of an input object is closely tied to the look of some real-world object, but the analogy ends there. For example, there are TUI systems in which a variety of physical shapes all share one recognized action, namely being brought near the computer in a "here I am" announcement. In this case, objects differ only in their look, sharing the same action. For example, in the system of Want et al. [68], a variety of objects possess distinct RFID tags—when they are bought to a computer, the computer performs some semantics cued to the shape and affordances of that object. The physical properties of the object are all that matters; all objects use the same gesture. Similarly, in the "Navigational Blocks" system [9], cubes are employed that have pictures and text on their faces. Selecting a picture (and, hence, a face of the cube) determines an operand to an operation. While almost every metaphor of noun we have seen employed has focused on an appeal to the visual aspect, others are possible as well: appeals to the sound, texture, etc. of an object. We are aware of only one probe into this space, a very new system [38] which analogizes the concept of "ammunition" in their system to the real-world sound a shotgun makes when being loaded

2B. Verb Conversely, in some systems, the analogy is to the act being performed (the "verb"), largely independent of the object it is being performed on—"<X>-ing in our system is like <X>-ing in the real world." TUI examples of this include the "Graspable Display" [59], in which the "push away" gesture maps to "reduce text point size", or the "SketchPad" system [35], where the "shake" gesture maps to "clear." The shapes of the objects are largely irrelevant; the analogy is to the gesture employed.

3. Noun and verb Noun and verb are now related, with an appeal to analogy, but the physical and virtual objects still differ—"<X>-ing an <A> in our system is like <X>-ing something <A>-ish in the real world." For example, in conventional HCI, this is the level reached by the "drag-and-drop" interface, where dropping a virtual icon into a virtual wastebasket "is like" dropping a physical file into a physical wastebasket—the file is deleted. A metaphor of this type is very powerful, as shown by the enormous success of the "drag-and-drop" paradigm. That paradigm also shows how carefully that power must be employed—the decision by Apple to vary the metaphor slightly for a floppy disk (dropping a virtual floppy disk onto a virtual wastebasket does not destroy it, but rather, ejects it) has been hotly debated for years. In the TUI realm, many TUI systems operate at this level, but the level of analogy is even stronger because the object being manipulated is itself physical. For example, in the "Urp" system [67], the objects being manipulated are 3-D blocks representing buildings in a landscape. As they are moved, they cast shadows on the virtual landscape beneath them—moving a block in their system is like moving a building in the real world. In the "ToonTown" system [57], physical avatars represent users of a chat room. These avatars are then located in a tilted board, which is analogized to an auditorium—as the avatars move away from the stage, or to the left or right of it, their audio quality is varied accordingly; changing your seat in their system is like changing your seat in the real world.

Full At this level of metaphor, the user need make no analogy at all—to their mind, the virtual system *is* the physical system: they manipulate an object and the world changes in the desired way, in what has been termed "Really Direct Manipulation" [15]. In conventional HCI, this level of metaphor is reached by pen computers—writing with a stylus on the document *is* altering that document. A TUI example of this is the "Illuminating Clay" [45] system. In this system, users see a piece of moldable clay representing a landscape. As they move the clay, computer-calculated characteristics of the landscape are directly projected on it. To the users, there is no analogy or metaphor necessary—deforming the landscape is deforming the landscape.

Figure 2 summarizes these levels, showing images from systems mentioned above.

The same system can embody different levels of metaphor in its different interactions. For example, in the Barney [61] system, a plush toy representing a dismayingly popular children's figure responds to having its eyes covered by playing peek-a-boo. This is a fully realized metaphor: covering Barney's eyes and then uncovering them is like doing the same action to a small child. However, in another part of the system, squeezing Barney's hand causes the system to randomly choose from a number of innocuous responses, such as singing a song. Here, the metaphor is weaker—squeezing a small child's hand does not typically lead to those responses.

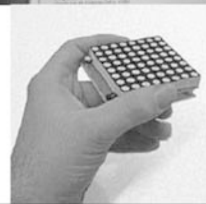
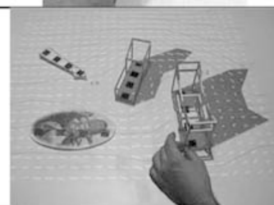
As this illustrates, care must be taken to match the metaphors closely, or else the powers of metaphor can weaken the value of the application, or require an extra level of learning. For example, in the "Bookmarks" system [68], a noun metaphor is employed—a physical bookmark is used to store a URL. However, to indicate the two verbs of getting and setting the bookmark, a different noun metaphor was employed. The top of the bookmark is used to indicate "setting" the bookmark, the bottom of the bookmark is used to indicate "getting" the bookmark, with the analogy being that of a funnel (things go in the top and come out the bottom). This confusion of two different noun metaphors resulted in a difficult-to-remember interaction. This illustrates that the level of metaphor is not "all or none"; various levels of strength (and conflict) are possible. As another example, in the "Doll's Head" [26] system mentioned earlier, the eyes on the doll's head led users to naturally conclude that their slicing gestures on the doll's head would be perfectly aligned with those in the MRI data probed by the slice: in fact, due to registration issues, this was not the case, and, in later versions, Hinckley [26] reduced the level of metaphor (B. Ullmer, personal communication, March 2004).

An advantage of promoting metaphor to a primary axis of TUI categorization is that it fosters application of the great body of knowledge about metaphor and its use from other fields. We cite five examples below, from five different fields, to give an idea of what we believe can be gained by broadening our domain of discourse:

Cultural anthropology Cultural anthropologists have studied how metaphors vary from culture to culture, knowledge which could improve TUI design. For example, Parikh et al. [43], testing a prototype TUI with rural villagers in India, found that the common use of red as a warning color was not effective. This is because the metaphorical binding of red to danger (analogized to blood) is one that only exists in certain Western cultures. In China, red is metaphorically bound to vitality/happiness (the analogy is to fire), in Japan, to warmth/light (the analogy is to the sun), and in this Indian culture, it had no metaphorical binding at all!

Evolution of cognition One aspect of TUI research has explored the power of metaphor. For example, Underkoffler and Ishii [67], outlining areas for future work, state that "the proposition of giving additional meaning and animate life to ordinary inert objects is a cognitively

Fig. 2 The levels of metaphor, with examples

Metaphor	Example	Picture
None	BitBeads	
Noun	Dictionary	
.. or Verb	Shaking	
Noun and Verb	Urp	
Full	Illuminating Clay	

powerful and intriguing one.'' Propositions such as this can be strengthened by drawing on results in the evolution of cognition, a cross-disciplinary blend of anthropology, archaeology, and physiology that studies the evolution of human cognition. We cited one of their results earlier, the belief that the ability to use metaphor is the defining cognitive characteristic separating early humans from modern humans. Another result is that ''the most powerful [metaphors] are those which cross domain boundaries, such as by associating a living entity with something that is inert...'' [40], corroborating and generalizing the TUI observation. By reinforcing and leveraging TUI design perspectives with results such as this from other fields, we can better ground and advance TUI design.

Cognitive psychology Cognitive psychologists have found that nouns and verbs appear deeply ingrained in our consciousness, even for deaf–mute children who are taught no sign languages [20, 21]. Furthermore, they nearly always express their concepts in metaphorical terms, even when higher-level sentence constructs such as adverbs and adjectives are used to modify the nouns and verbs [58]. These results led us to choose ''metaphor of noun'' and ''metaphor of verb'' as the levels for the ''metaphor'' axis. Furthermore, there is a consistent ordering to the gestural sentence structure [16] across wildly disparate user populations: for multi-gestured TUIs, adherence to this grammar could increase the naturalness of the interface.

Industrial design Industrial designers have decades of experience in how, when, and whether to employ metaphor. Gorbet [22] provides two examples of how their lessons can be used as inspiration for TUI design. First, he argues (by analogy to industrial design involving plastics) that the most compelling and interesting TUIs will be those which employ *no* metaphor, as they are the most free from the constraints of imitation. Ullmer (personal communication, March 2004) similarly found, when designing the ''Illuminating Light'' system [66], that an overly literal metaphorical presentation reduced user comfort. Second, Gorbet [22] uses the investigation of ''product semantics'' in industrial design (examining the employment of metaphor in the design of everyday objects, such as toasters, TV sets, and answering machines), to illustrate the trade-offs of higher and lower levels of metaphor. Whether one agrees with the "no metaphor" argument or not, it provides an example of the kind of principled argumentation and inspiration that we can draw from industrial design knowledge.

Philosophy of science Exactly because metaphor has such cognitive power, it should be employed with care. Philosophers of science warn against over-reliance on metaphor: "attachment to a particular model can inhibit thinking in other, possibly more productive ways about the system being studied" [8]. This is synergistic with Gorbet's and Ullmer's experiences related above.

We believe that there is no "one size fits all" answer as to when metaphor should be employed in a TUI. Our point is simply that, by paying attention to this choice, more effective designs can be made. If the goal is for the lowest cognitive overhead, the operations on the object do in fact match very well with those of the analogized object, and re-use of the object across application domains is not necessary, then a high use of metaphor is appropriate. Conversely, if the object is a general-purpose one, one which should cognitively lend itself to any number of situations, then less metaphor should be used, as was done in for example the "Bricks" [18] system. In sum, once metaphor is made an explicit and major focus of TUI design, then we can leverage the received wisdom from many fields.

4 Utility of the taxonomy

We have presented the taxonomy, and argued that its axes are well suited for describing and designing TUIs. For example, this is the first TUI taxonomy that we are aware of with axes that lend themselves naturally to discussions of design principles and trade-offs. In this section, we further motivate this taxonomy. We do so by showing that previous formalisms, distinctions, and genres are accommodated within it, and that it reveals a previously unconsidered trajectory to the evolution of the field:

4.1 Tools, tokens, and containers

Holmquist et al. [27] categorize TUI artifacts into one of three categories: containers, tool, or tokens. *Containers* are defined as "generic objects used to move information between different devices or platforms." In our formalism, we can say that these are artifacts which are *fully* embodied (the information is considered to "live" within an object), and which use a particular metaphor of *verb* ("moving the container is like moving data"). By choosing not to employ metaphor of noun, the container retains the generality and flexibility of being able to carry any type of data, but at the cost of a slight cognitive overhead.

Tools are defined as things which "actively manipulate digital information." In our formalism, we can say that these are artifacts are *nearby* embodied (the tool manipulates something next to its surface of action: e.g., a digital desk [18, 67], or the display on a tablet [25]). The metaphorical level varies. In the system of [25], bringing a French–English dictionary to a table computer invoked a translation service: the metaphor is that of *noun* (the dictionary). In the "Bricks" [18] system, bricks can be bound to various concepts, but, most typically, are bound to a vertex or endpoint. Performing operations on the lines formed by those points, or on the vertices themselves, mimics those operations as performed in plane geometry; the metaphor is that of *verb*.

Tokens are defined as "objects that physically resemble the information they represent." This is analogous to our *metaphor of noun*.

Figure 3 shows the space these three terms occupy in our taxonomy; we can easily and immediately confirm the observation of [27] that containers and tools can also be tokens. For example, in the "Urp" system [67], as in the Bricks system [18], objects placed on a digital desk were used to indicate operations on that desk. However, unlike in the Bricks system, the objects were themselves bound to particular shapes—the shapes of buildings. In our notation, we have, therefore, moved from *metaphor of verb* to *metaphor of noun and verb*.

4.2 "Object as..."

In 1999, Underkoffler and Ishii [67] proposed a classification system for objects employed in a TUI. We now show how those are accommodated within this taxonomy (Fig. 4):

- *Object as noun*. This is equivalent to our "metaphor of noun."
- *Object as verb*. This is equivalent to our "metaphor of verb."
- *Object as reconfigurable tool*. In this case, the semantic meaning of manipulating the object can change over time. We view this as a special type of the "tool" of Holmquist et al. [27], discussed above, where no metaphorical binding is fixed. This type of object is a "nearby" embodiment object, with "none" metaphor.

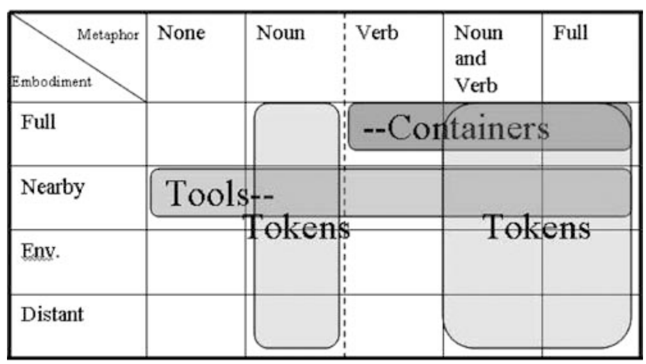


Fig. 3 The categories of [27] as they relate to our taxonomy

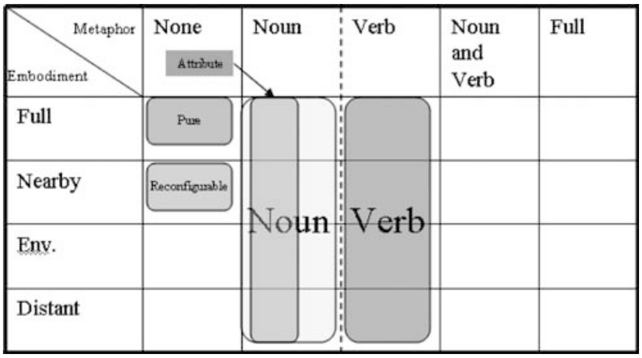


Fig. 4 The "object as" classification, as it relates to our taxonomy

- *Object as attribute*. This is a weaker type of "metaphor as noun", where *only one* attribute of the object's shape is used in the analogy: the object color, size, or shape, but no more than one of these.
- *Object as pure object*. Here, "information can be stored in arbitrary objects." This is a variation of the "container" of Holmquist et al. [27], discussed above. It employs embodiment of "full" (the information is stored *in* the object), with metaphor of "none" (the physical representation of the object is irrelevant, and no particular gestures are necessarily valid).

4.3 Calm computing

We mentioned earlier, in our three-step sequence, that the input is "typically" a physical manipulation by a user. What type of interfaces result when input is *not* a physical manipulation by a user? In this case, we wind up with exactly the set of experiences termed "calm computing." These experiences (it's not clear they are really "user interfaces," as they often involve no user input) are designed precisely to give physical output to a user, without that user performing explicit physical input.

This limits and alters the interaction, but the axes still apply. This allows us to disentangle and integrate calm computing, as has not been done before. For example, at one extreme, consider calm systems which have an embodiment of "distant." This means a calm system which is reflecting a physically distant input event. Systems such as Wellner et al.'s "live wire" [70], or Mankoff et al.'s [37] bus mobile, are in this category. Both employ metaphor of verb: "live wire" analogizes a moving wire to the motion of network traffic, while in the bus mobile, shortening a string is analogized to shortening the wait for a bus.

Moving to "environmental" embodiment, we have systems which respond to environmental conditions such as sound. The flower of [2] is an example of this; flower petals move up and down in response to room sound levels, in a very rough metaphor of verb ("raising sound level raises petals").

"Nearby" calm systems are rare; this would be a system which does not take explicit user input, and yet, responds to something else touching it. We are not aware of any calm experiences in this category—a potential interesting area of exploration.

At the "full" level of embodiment, we have calm systems which take no explicit physical user input, yet display a changing internal state: a "lava lamp" is an example of such a system.

We therefore see how this taxonomy can easily accommodate and locate calm computing within the TUI realm by relaxing the requirement that the input be an explicit user physical gesture. For the remainder of this paper, for greater focus, we re-instate the requirement.

4.4 Generic vs. representational

In his Masters thesis, Gorbet [22] also briefly discusses the importance of metaphor for TUI design. He presents, as we do, a 1-D axis for metaphor, ranging from "generic" (our "none") through "representational" (our "metaphor of noun and verb"). His axis, while shown as open-ended, doesn't mention the "full" state (where we go "beyond metaphor").

4.5 Existing samples from industrial design

At the beginning of the paper, we presented a number of TUI-ish artifacts present in the existing world of design, and postulated that any TUI taxonomy should be able to incorporate them. Indeed, our taxonomy can include:

Greeting-card audio Cards that play a song when opened have an embodiment of "environmental." The metaphor is that of verb: receiving a written message is like receiving an audio message.

Joysticks Computer joysticks shaped like steering wheels have embodiment of "distant" (the effect happens on the computer screen), with metaphor of "noun and verb": operations on a wheel-shaped joystick are like operations on a steering wheel. If the joystick is no longer shaped like a steering wheel, the metaphor is lowered to that of "verb": "moving the stick to the left moves the thing I am controlling to the left." Finally, a computer keyboard has embodiment of "distant," and metaphor of "none." This again illustrates that each of these areas has their own design niche; by being aware of their design goals, we can be guided as to which part of the TUI spectrum is best suited for them.

Shaped car-seat controls Car-seat controls shaped like car seats have embodiment of "nearby" (they are typically placed directly next to the car seat), and, again, metaphor of "noun and verb": operations on a small car-seat-shape are like operations on a car seat. Voodoo dolls, similarly, have metaphor of "noun and verb," and embodiment of "distant."

Figure 5 shows these artifacts, and a few others, placed within our taxonomy. Note that as we move towards the "full"/"full" corner, the artifacts become more like TUIs, in a natural way:

4.6 Evolution of the field

We believe this taxonomy is also of use in revealing previously un-remarked trends in the evolution of TUI research. To allow for meaningful comparison, we decide to analyze only systems which dealt with the same task domain. Owing to the exploratory nature of research, we were surprised to find that, in the over 60 TUI systems we examined (the bibliography has a complete list), there were only a few which returned to the task domain of an earlier paper. Specifically, we found three such task domains:

Children's storytelling In the "StoryMat" system [51], children interact with a physical device on a play mat. As they move the device about, and tell a story out loud, the story is recorded. At a later time, the story can be played back, with the audio being reproduced, and the video being done by a projected animation. By our categorization, this has embodiment of "environment" (the audio feedback) and "nearby" (the video), and metaphor of "metaphor of noun and verb" (moving a toy in the physical world later moves a projected replica of the toy in that same physical world). The next year, the "CurlyBot" [19] system was presented. Here, children again interact with a physical device on a play mat. Again, as they move the device about, the motions are recorded. At a later time, the motion can be played back. This varies from the first system by having an embodiment of "full" (the output device is the input device; it reproduces its earlier motions), and a "metaphor of noun and verb" (the user moves a toy in the physical world; later, the toy moves itself in that same physical world). Recently, the "Topobo" [46] system was presented, which builds on the "CurlyBot" system by having the toy move itself at all stages—the user moves the legs of the toy, teaching it a locomotion sequence.

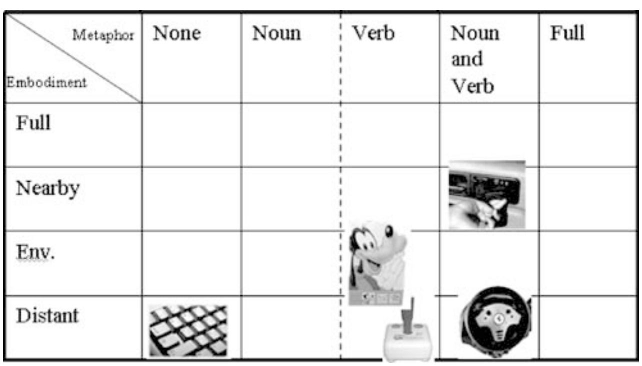


Fig. 5 Industrial design artifacts placed in the taxonomy

The toy then moves itself in the physical world as per that sequence. The level of embodiment has stayed the same, but the level of metaphor is now "full"—the toy no longer moves in imitation of a path traced by an outside agent, it has now been "taught to walk" and moves about itself.

Tangible workbenches In the "Illuminating Light" system [66], users move blocks about an augmented table. As they move the blocks about, the blocks serve as perfect reflectors, and light rays are shown on the table showing how the light paths vary as the reflectors are moved. By our categorization, this has embodiment of "nearby" (the light paths typically touch the blocks), and metaphor of "metaphor of noun and verb" (moving a block in the system is like moving a reflector in the real world). The next year, the "Urp" system [67] was presented. Again, the users moved blocks about the table, and again, optics were simulated. However, now the blocks are 3-D objects, which cast virtual shadows, interact with each other, and so forth. The system has increased its metaphor by more tightly metaphorically binding the physical characteristics of the objects. Two years later, the "Illuminating Clay" system was presented [45]. Now the blocks have gone, and users manipulate a landscape by physically manipulating a clay model. The system has reached full embodiment and full metaphor.

Control widgets on an augmented desktop In the "Bricks" system [18], users employ physical bricks on an augmented desktop. As users move bricks about the desktop, they send control messages to the objects beneath them—to reposition geometric shapes, perform rotations, etc. In this case, the embodiment is "nearby," and the metaphor is "verb"—"rotating the line formed by two bricks is like rotation." Five years later, the "ToolStone" [48] system revisited this task domain. Now, the physical objects employed are unique 3-D shapes—the system pays attention to which sides of the shapes are facing the desktop, and different stones have different shapes. The levels of embodiment and metaphor are still "nearby" and "verb"—the unique shapes of the ToolStones are not analogized to any real-world physical objects. The next year, the "DataTiles" system [49] revisited this task domain. The control objects are now transparent tiles. The shapes and locations of the tiles are important; they work rather like physical magic lenses [5] over the appropriate section of the desktop. In this case, then, the embodiment has moved almost to "full" (since the tiles are transparent, the user can now largely conceive of the tiles as being "melded" into the work surface), and the metaphor has moved to "noun and verb"—filtering a part of the view in their system is like filtering part of a view in the real world.

In Figure 6, we have tabulated the evolutions of these three task domains in our taxonomy. This reveals that, in all three task domains, the trend has been to increase

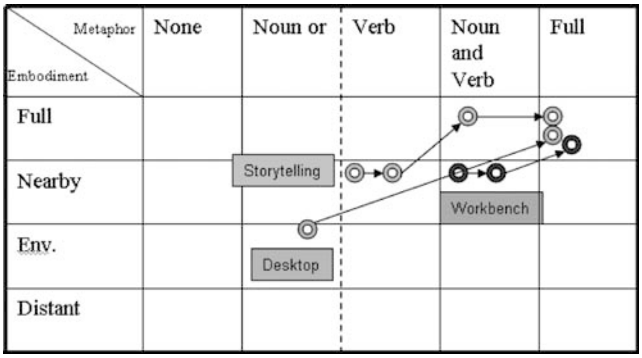


Fig. 6 The evolution of TUIs, as plotted in our taxonomy, for three different task domains

the levels of embodiment and metaphor. Interestingly, this trend reaches towards the corner highlighted earlier as that occupied by the intersection of the Holmquist "tokens" and the Holmquist "containers" [27]. A busy and fruitful corner! As the field matures, we are sure to see other such trajectories and sweeps.

5 Conclusions

We have defined, discussed, and analyzed TUIs. A novel taxonomy for them has been proposed that: unifies several previous frameworks; naturally lends itself to design principles to guide future work in the field; reveals new structure in the history of the work in the field; incorporates "calm computing"; and seamlessly integrates "more tangible" interfaces with "less tangible" ones, all the way down to the mouse and keyboard.

There are many interesting areas for future work. The dimension of metaphor laid out one particular way to linearize that dimension: there may well be other, more useful (perhaps multi-dimensional), orderings. Another open question is how/whether the model in this paper can be best integrated with the complementary "MCRit" model of Ullmer and Ishii [65], which operates at a higher level of abstraction.

Tangible user interfaces have received much excitement and attention. We believe this is because, at core, they are leaving the conventional computer virtual world, and taking steps into the physical world. However, it is time to realize the implication of that step—it leads away from computer–human interfaces and into the realm of human interfaces *in general*. When this happens, the fields of discourse change. We hope that future TUI papers will draw less from their point of departure in the computer science community and more from their point of arrival—the communities of industrial design, kinesthesiology, architecture, and anthropology.

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