ABSTRACT
An important and long-standing goal of interaction design is to make interfaces invisible. Effective interaction design in embodied computing must map the inputs and outputs of the computational process with the qualities of the physical artifact in which it is embedded, taking into account qualities such as size, shape, texture, material, and geometry. To go beyond ad-hoc demonstration projects, style guides, pattern languages, and toolkits, a principled approach to designing embodied interaction is needed. We present in this paper a collection of physical computing projects that leverage our understanding of physicality of objects and describe principles and classifications that link them together.

Categories and Subject Descriptors
H.5.2 [Information Interfaces and Presentation]: User Interfaces – evaluation/methodology, haptic I/O, interaction styles, style guides, theory and methods

General Terms
Design, Human Factors, Languages, Theory

Keywords
 número, physical, design method.

1. COMPUTATIONAL AND PHYSICAL DESIGN
As computation moves beyond the screen into the physical world we inhabit, the dimensions of interaction design expand to include the domain of industrial designers and architects. Effective design of embodied computational systems depends on understanding, then mapping, their physical and computational characteristics. Many are now developing artifacts that employ tangible interaction, mixed and augmented reality, ubiquitous computing. These first generation, ad-hoc one-off investigations are novel and intriguing indicating a rich and large universe of possible designs. How can we understand the relationships between the physical and computational characteristics of these hybrid systems? Can we develop more systematic ways of making design decisions?

1.1 Real direct manipulation
Over the twenty-five years in which windows–mouse–menu interaction has dominated, users have developed expectations for screen-based interaction and accordingly, guidelines for the appropriate design of screen based computational artifacts. These are codified in UI guidelines, accessibility standards, and conventional wisdom and prejudice. However, little of this is useful when designing physically embedded computational artifacts.

In “direct manipulation” users select screen objects with a mouse and edit them or apply operations with tools chosen from a nearby palette. Yet compared to, for example, a pen-based drawing environment where one simply draws what one wants, a mouse-menu interface to a draw program seems a terribly indirect way to manipulate the objects in one’s world. Today we are on the threshold of real direct manipulation. The objects you manipulate in the physical world are the objects themselves, not graphical depictions of them. Physicality is a sort of meta-interface and the mapping of a physical object to a task is often more obvious than mapping of a GUI depiction (e.g., a menu) to that task. Endowing physical objects with computational capabilities allows a rich interaction without the traditional GUI trappings such as menus—an invisible interaction.

1.2 Beyond toolkits and style guides
Many are working on toolkits for tangible interaction [4,5,6], which provide the techniques of implementing embodied computational systems. Inspiring metaphor [3] has a role to play too. Efforts focused at supporting existing work practice (e.g., [7]) with computationally augmented physical artifacts can follow domain conventions. What’s needed is a more systematic understanding of how qualities of the physical world can map to the inputs, outputs, and side-effects of computations. First efforts in this direction might be pattern-language-like compendia of ‘best practices,’ or style guides. However, we believe it possible to develop more formal approaches to specifying, testing, and eventually implementing embodied computation. One might imagine a design language for specifying hybrid physical-computational systems. Such a language would need to take into account both the computational behavior as well as the physical characteristics of designs. We are aware that this is an ill-defined challenge; in the following we indicate some preliminary thoughts based on our experience with implementing several small physical computing artifacts.
2. EXAMPLES

Over the past few years, students and researchers in our group have built a set of computationally enhanced physical objects. They range from small class term projects in a course [2] (many of them art pieces) to more extended efforts. They have helped us to think concretely about the design of physically embedded computing artifacts and environments. We describe several of these projects as a starting point for some observations about the design of artifacts of this type.

2.1 Navigational Blocks

Navigational Blocks [1] are a tangible user interface that facilitates retrieval of historical stories from a multi-media database. Each face of the block represents a subcategory. For example, the Who block has a face representing the founding father, and another face the merchant. A face of the What block represents an historical event and a face of the Where block represents a location. Orientation, movement, and relative positions of wooden blocks provide a physical embodiment of digital information through tactile manipulation and haptic feedback. Electromagnets embedded in the Blocks and wireless communication encourage rapid rearrangement to form different queries into the database.

![Figure 1. Navigational Blocks as query interface to multi-media database of historical stories](image1)

2.2 FlexM

FlexM is a hub-and-strut toy for making and manipulating geometric models with computer models and simulations. Sensors and microprocessors embedded in the hubs determine the topology and geometry of the model the user assembles. With flexible joints on the hubs, the designer can make models that transform dynamically. The hubs transmit parametric information to the computer, which renders the model on the screen in real time. This allows the designer to create complex forms with the fun and directness of playing with a toy.

2.3 Computational Books

A paper pop-up book with light sensors embedded in its pages is linked to a desktop computer. When the reader operates the pop-up features (by pushing or turning a strip of paper), one of the light sensors is exposed to ambient light in the room. The microcontroller in the book notices this, and relays information to the desktop computer, which augments the story on the pop-up book page with a video or audio supplement.

2.4 MouseHaus Table

MouseHaus Table is an interface to pedestrian movement simulation. It uses a video camera to capture images of paper cutouts representing urban elements on a table, as collaborating designers add, remove, and rearrange them to propose configurations of buildings, streets, and parks. A visual simulation of pedestrian behavior is projected on top of these arrangements, allowing the designers to understand the effects of their proposed arrangements. Instead of using a structured editor to input urban elements, MouseHaus Table users cut out colored paper with scissors and arrange them on the table to trigger real-time simulation feedback.

2.5 Window Seat

Window Seat is a chairware interface to control remote camera motion. It uses the rock and swivel of a chair as an interface for a pan and tilt camera. A rocking chair controls the up/down tilt and pressure sensors control the left/right pan. A tiny camera is placed inside an architectural model, and a projector mounted inside the chair and a mirror displays the camera’s current viewpoint on the wall in front of the chair. By controlling the camera the chair’s occupant virtually occupies a scale model or remote space.

![Figure 2. Window Seat rocking chair's up/down and left/right motion controls a remote camera.](image2)

2.6 Laser Space

Laser Space uses low power laser light to create the sensation of a bounded but nonphysical space. A DC motor spins an angled mirror to reflect a laser beam, forming a cone made visible by a fog machine. A break-beam sensor composed of a laser (visible as a red line of light) and a photocell “opens the door” when a person approaches. A servomotor interrupts the cone with a wedge to create a visible entrance.

2.7 Plant Tiles

Plant Tiles controls video playback by people's movement on the floor. A six by ten foot platform sits in front of a rear-projected screen showing time-lapse video of plant growth. When you step onto the platform, a projected video sequence plays to a key frame. Walking toward the screen plays the sequence forward; walking backward reverses it. Side to side movement triggers different video segments.
2.8 Alphabet Paint Space

Alphabet Paint Space uses people’s motion as “brushes” to create a painting. A video camera captures images (15 frames per second) of people moving through the space. The processed images, which depict an abstraction of the movement, then project onto a large screen at one end of the hall. The resulting light-painted mural traces movement that fades slowly over time. The mural constantly evolves, reflecting the current state of the space.

Table 1 summarizes the input and output modes of these projects. Input mode is strongly structured by project size—manipulation for object size, gesture for body size, walking for room size. Output mode for most projects uses an adjacent screen or projector, regardless of size; only a few (especially the Laser Space project and the Jungle Room) don’t use a video display but rely on alternative output media.

![Image](image.png)

Figure 1. Floor tile sensors create an interactive platform space in PlantTiles.

Table 1. comparing size, input, and output modes

<table>
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<tr>
<th>Project</th>
<th>Size/Scale</th>
<th>Input</th>
<th>Output</th>
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<td>Navigational Blocks</td>
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<td>orientation, arrangement</td>
<td>screen, display</td>
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<tr>
<td>FlexM</td>
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<td>Alphabet Paint Space</td>
<td>room</td>
<td>walking, gesture</td>
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3. PHYSICAL QUALITIES

3.1 Size and scale

People relate quite differently to artifacts of different sizes:

The smallest is **object-size**. We have an intimate relationship with objects or things—jewelry, plates, pens, toys—we can pick up and hold in our hands, caress, squeeze, throw against the wall, and so on. The scale of interaction is hand manipulation.

Next up is **body-size** things that are more or less the same size as we are: tables and chairs, clothing, bicycles, and we relate quite differently to body-size objects, though still intimately, than we do to smaller objects. The interaction at this level often involves our body postures or positions.

When artifacts become much larger than ourselves, again we relate to them differently, no longer as objects, but now as spaces we inhabit: the **room-size**. This brings in questions of territory and control, of the presence of others, and our movement through and around the space becomes an important factor.

At the top of the scale is the **city-size**. Here we are citizens, the spaces we move through are for the most part in the public realm. We cannot exercise individual control of this space, except perhaps for short periods of time. We share it with others whom we do not know and there our actions are open to the scrutiny of all.

3.2 Form

The form of a physical artifact suggests ways of interacting with it: a surface at 42cm invites sitting; a cord invites pulling; a button invites pressing. Without trying for completeness, we might list some of the characteristics or qualities of physical artifacts, which a designer must consider and ultimately decide about. Among these “form” qualities are:

- Material: what is it made of? (e.g., plastic, aluminum, steel, wood, paper) is it hard, soft, warm or cold to the touch, rigid, springy, or flexible, hollow or solid?
- Appearance or presentation: how does it look? what color is it? how does it sound? does it smell? etc.
- Shape: what is its overall shape? is it round and blobby or square and sharp-cornered? Is it a single shape or a network?
- Assembly: is it made up of recognizable parts?
- Connotations and attachment of meanings: what are the form’s cultural messages?

These qualities obtain at all the sizes mentioned above. For example, at the room scale, a classroom or meeting space has a recognizable shape and appearance; it has certain parts (a black or whiteboard, desks or a meeting table, chairs), cultural meaning (we easily distinguish the company boardroom from a university seminar room). Decisions that the designer makes about these physical qualities affect, even control, our understanding, our emotional response, and the way we interact with one another and the space itself.

4. COMPUTATIONAL QUALITIES

What qualities of computational artifacts must interaction designers consider and ultimately decide about? Computation allows us to map objects to tasks at the design or intentional level rather than merely the physical level.

Computational artifacts are processes, perceivable qualities of which are inputs, outputs, and side-effects. We may be unaware that the computational system is gathering inputs, and it may modulate its outputs in ways that we don’t
explicitly notice. A system to support Alzheimer’s patients might observe identities of people in the room and tailor its presentations accordingly, behaving differently when a caregiver is in the room from when only a patient is present. No one attends specifically to the input, which may be mediated by fairly sophisticated processing. Even when we are unconscious of the ongoing computation, still the design of computationally embedded artifacts and spaces requires mapping inputs and outputs to physical sensing and control.

4.1 Inputs and outputs
To effect outputs in screen-based interaction, the UI designer is limited to graphical and audio means: the familiar widgets and earcons. In designing physically embedded computational artifacts, the gamut expands to ambient displays that use, for example, light, color, shadow, background sound to express information. Today, flat and often high-resolution screens are embedded into objects (cell phones, PDAs) and rooms (display walls), and some specialty high-tech furniture (tables). As well, the designer may control physical characteristics of materials, for example elasticity, opaqueness, or move physical components, for example opening doors or windows in a building.

Computational tools are designed to help people perform intended tasks. These tools present an interface. Unlike their non-computational cousins, computational tools may intend to complete tasks. To recognize and use a tool one must map its interface to the task one seeks to perform. Physical embodiment of computation enables the interface to become invisible by leveraging our experience with everyday objects. The physicality of these interfaces can allow people to take advantage of computational systems, without devoting attention to the interaction.

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6. REFERENCES