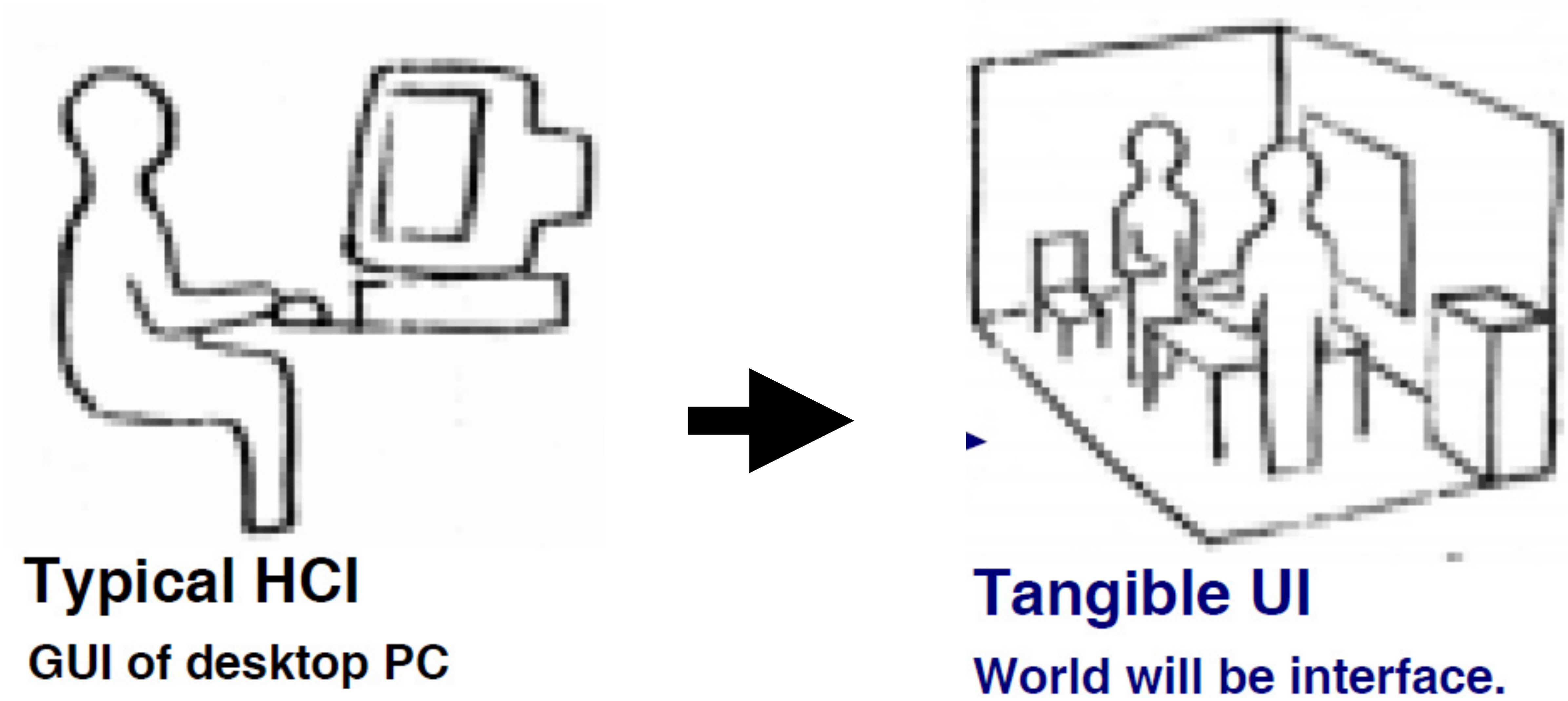
Tangible Computing

6.S063 Engineering Interaction Technologies

Prof. Stefanie Mueller | HCI Engineering Group



1997: Ishii: long term vision for Tangible User Interfaces

Tangible Bits [Ishii UIST'97]

Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms

Hiroshi Ishii and Brygg Ullmer
MIT Media Laboratory
Tangible Media Group
20 Ames Street, Cambridge, MA 02139-4307 USA
{ishii, ullmer}@media.mit.edu

ABSTRACT

This paper presents our vision of Human Computer Interaction (HCI): "Tangible Bits." Tangible Bits allows users to "grasp & manipulate" bits in the center of users' attention by coupling the bits with everyday physical objects and architectural surfaces. Tangible Bits also enables users to be aware of background bits at the periphery of human perception using ambient display media such as light, sound, airflow, and water movement in an augmented space. The goal of Tangible Bits is to bridge the gaps between both cyberspace and the physical environment, as well as the foreground and background of human activities.

This paper describes three key concepts of Tangible Bits: interactive surfaces; the coupling of bits with graspable physical objects; and ambient media for background awareness. We illustrate these concepts with three prototype systems – the metaDESK, transBOARD and ambientROOM – to identify underlying research issues.

Keywords

tangible user interface, ambient media, graspable user interface, augmented reality, ubiquitous computing, center and periphery, foreground and background

INTRODUCTION: FROM THE MUSEUM

Long before the invention of personal computers, our ancestors developed a variety of specialized physical artifacts to measure the passage of time, to predict the movement of planets, to draw geometric shapes, and to compute [10]. We can find these beautiful artifacts made of oak and brass

BITS & ATOMS

We live between two realms: our physical environment and cyberspace. Despite our dual citizenship, the absence of seamless couplings between these parallel existences leaves a great divide between the worlds of bits and atoms. At the present, we are torn between these parallel but disjoint spaces.

Figure 1 Sketches made at Collection of Historical Scientific Instruments at Harvard University

We are now almost constantly "wired" so that we can be here (physical space) and there (cyberspace) simultaneously [14]. Streams of bits leak out of cyberspace through a myriad of rectangular screens into the physical world as photon beams. However, the interactions between people and cyberspace are now largely confined to traditional GUI (Graphical User Interface)-based boxes sitting on desktops or laptops. The interactions with these GUIs are separated from the ordinary physical environment within which we live and interact.

Although we have developed various skills and work practices for processing information through haptic interactions with physical objects (e.g., scribbling messages on Post-It™ notes and spatially manipulating them on a wall) as well as peripheral senses (e.g., being

tangible UI::

- give **physical form** to digital information
- users **interact through a physical representation** with digital information

is this a tangible UI?

<30s brainstorming>

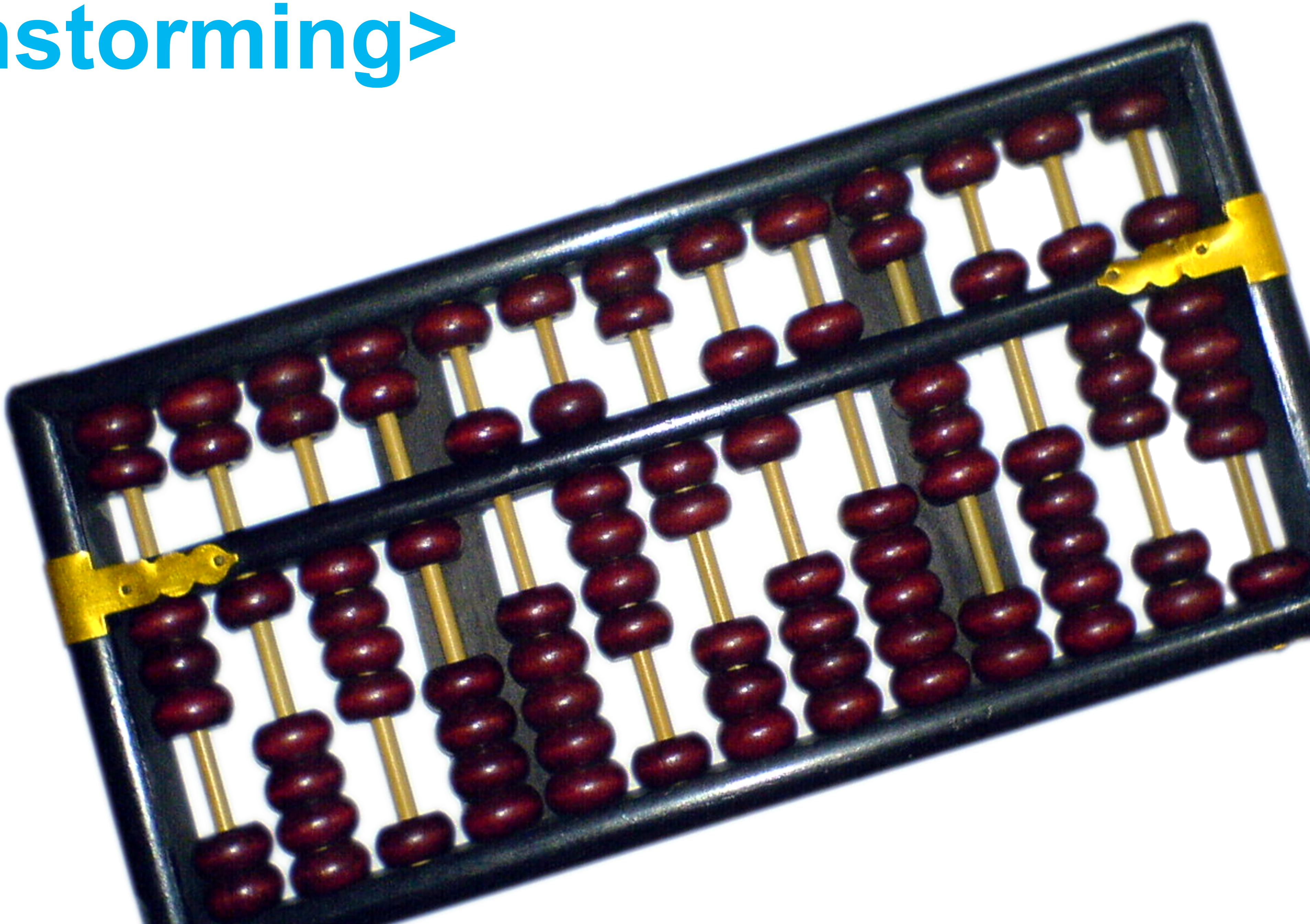
is this a tangible UI?

no, does not **represent digital information**

(it is a generic input device)

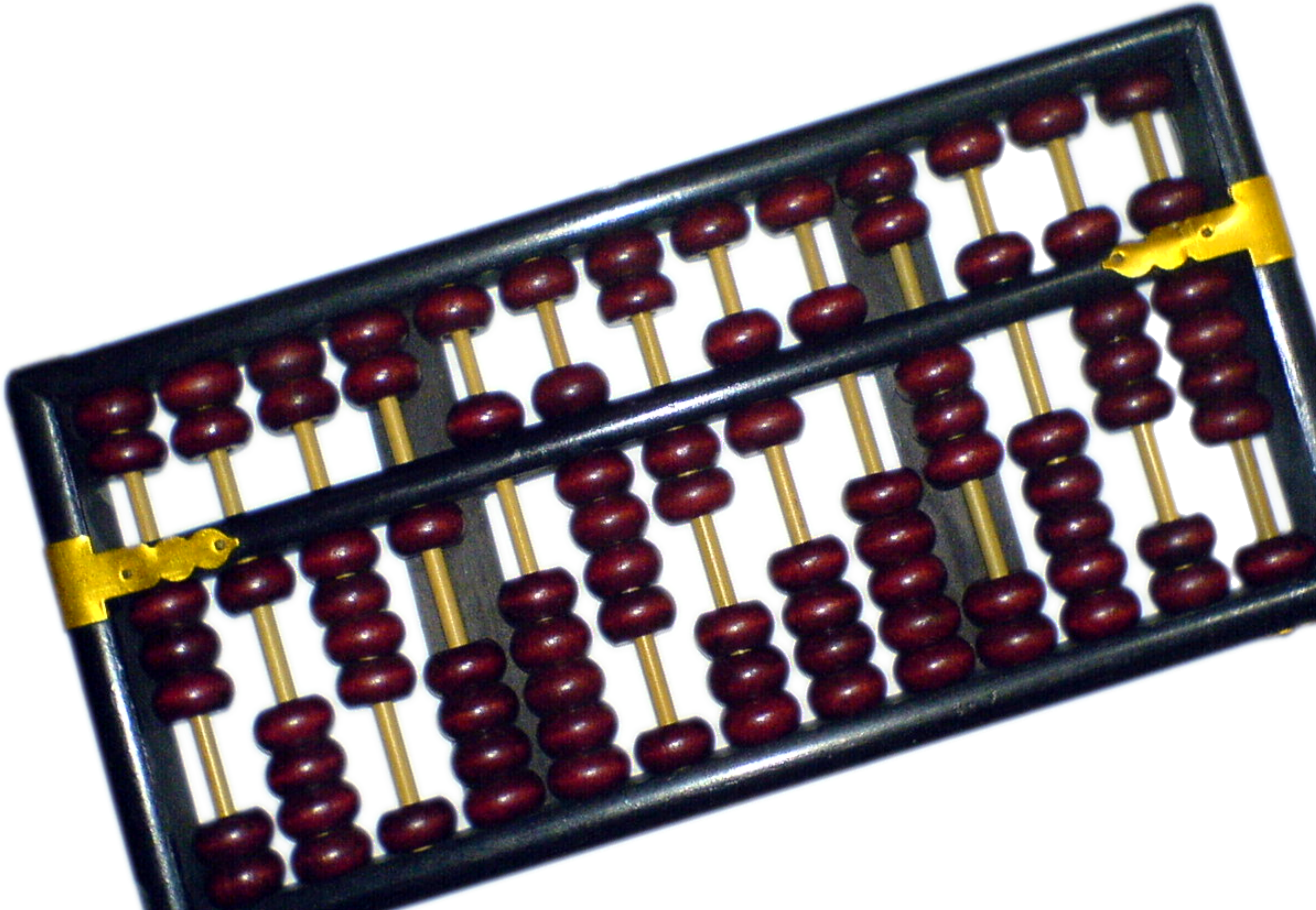
is the abacus a tangible UI?

<30s brainstorming>



is the abacus a tangible UI?

no, it's analog, there's no coupling to **digital** information



is this a tangible UI?

<30s brainstorming>

i/o brush [Ryokai,CHI'04]

is this a tangible UI?

yes, users interact with a physical representation that represents digital information **(digital brush & painting color)**

I/O Brush: Drawing with Everyday Objects as Ink

Kimiko Ryokai, Stefan Marti and Hiroshi Ishii
MIT Media Laboratory
20 Ames Street
Cambridge, MA 02139 USA
{kimiko, stefanm, ishii}@media.mit.edu

ABSTRACT
We introduce I/O Brush, a new drawing tool aimed at young children, ages four and up, to explore colors, textures, and movements found in everyday materials by "picking up" and drawing with them. I/O Brush looks like a regular physical paintbrush but has a small video camera with lights and touch sensors embedded inside. Outside of the drawing canvas, the brush can pick up color, texture, and movement of a brushed surface. On the canvas, children can draw with the special "ink" they just picked up from their immediate environment. In our preliminary study with kindergarteners, we found that children not only produced complex works of art using I/O Brush, but they also engaged in explicit talk about patterns and features available in their environment. I/O Brush invites children to explore the transformation from concrete and familiar raw material into abstract concepts about patterns of colors, textures and movements.

Categories & Subject Descriptors: K.3.2 [Computers and Education]: Computer and Information Science Education

General Terms: Design, Experimentation, Human Factors.

Keywords: Children, Drawing, Building Blocks, Explaining, Storytelling, Input Device, Toy, Tangible User Interface.

INTRODUCTION

Creating visual art—the process of choosing colors, determining where a line should go, selecting shapes, and

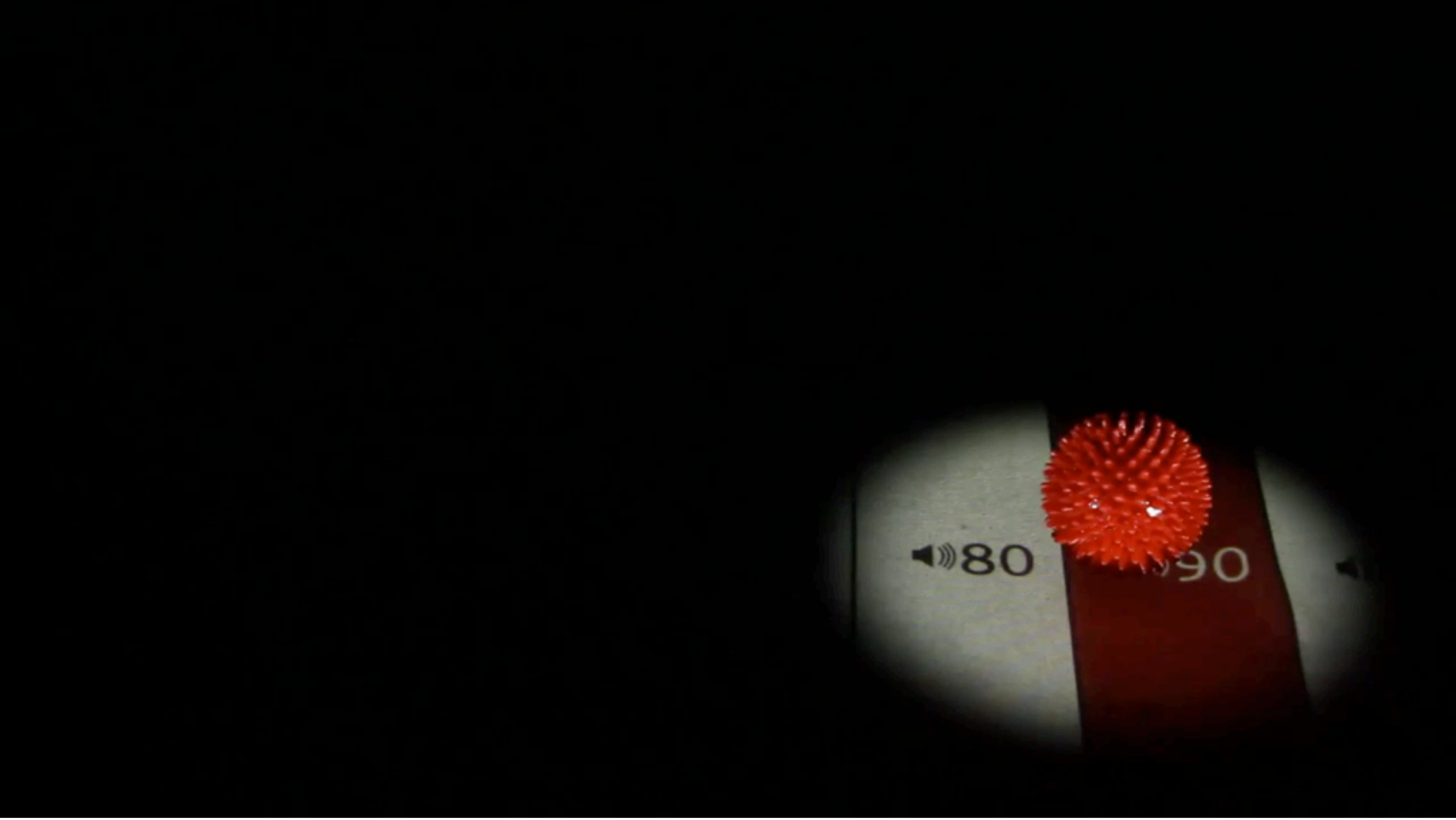
paper and allows them to reflect on their thoughts through abstract representations [32].

Yet the success of such abstract thinking may depend on how it is grounded in the child's own reality. Indeed, school oriented (namely American middle-class) parents make great efforts to create connections between new concepts and real life by talking about them (e.g., "The duck in this book is yellow, just like the one in our tub!") [14]. The new information the child is trying to make sense of needs to be grounded in some reality to be useful, but cannot be if it hasn't been acquired in terms of that reality [28]. Therefore, learning to deal with new concepts while staying connected with familiar surroundings and objects seems to be important in developing new skills.

In this paper, we discuss a novel approach to this important connection. We present I/O Brush, an augmented paintbrush that can pick up textures, colors, and movements from the real world, and allows children to immediately use, explore and make drawings with them. We will discuss I/O Brush's potential as a tool to support young children's transformation from concrete and familiar material into abstract representations in visual art projects.

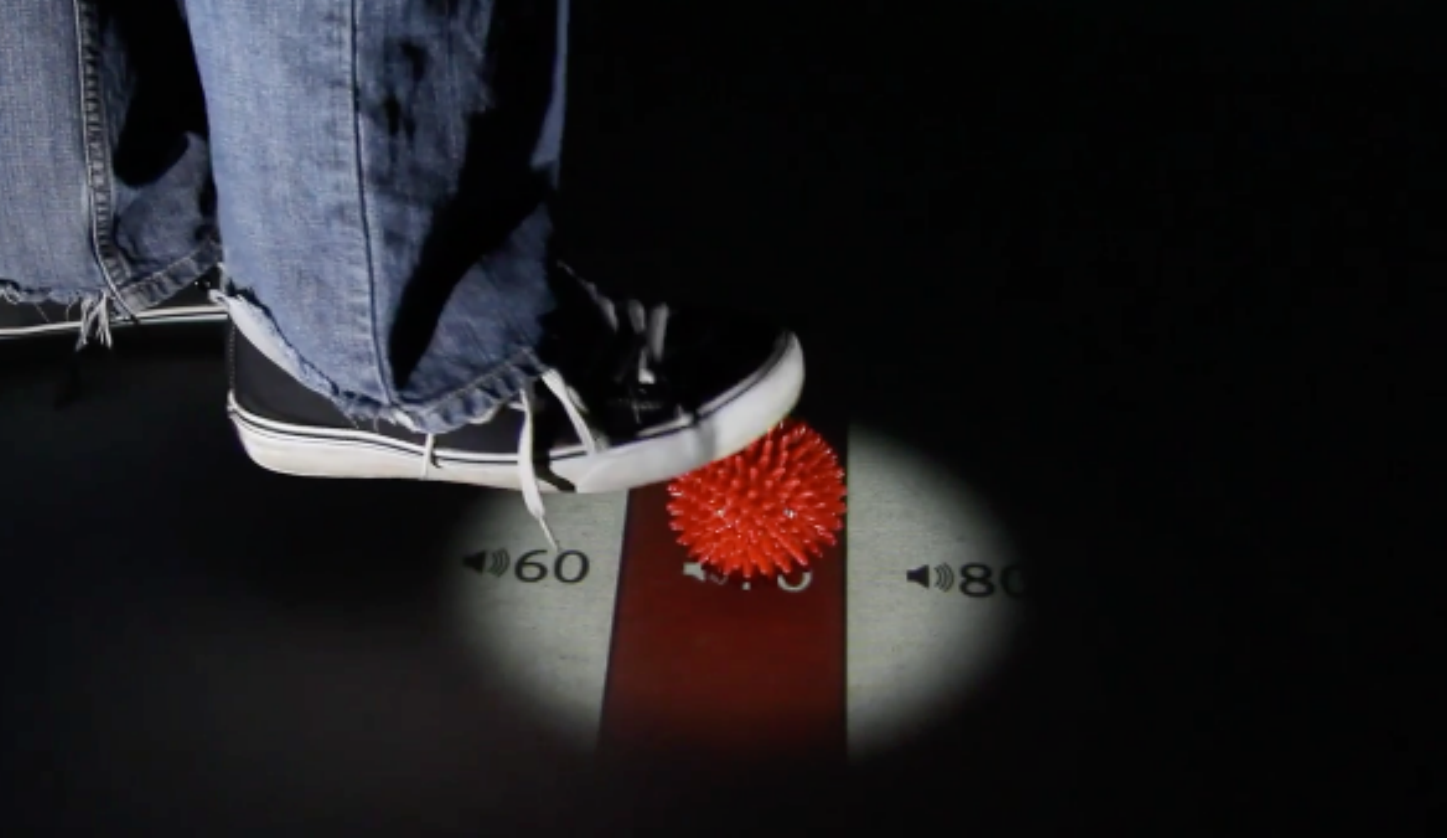
Taking Samples from the Real World

There are many sophisticated, commercially available drawing tools designed for children today. KidPix [19] is



is this a tangible UI?

<30s brainstorming>



is this a tangible UI?
hard to say, Ishii at CHI: **‘no,** it’s a **mouse pointer for feet’**

Kickables: Tangibles for Feet

Dominik Schmidt, Raf Ramakers[1], Esben W. Pedersen[2], Johannes Jasper, Sven Köhler, Aileen Pohl, Hannes Rantzsch, Andreas Rau, Patrick Schmidt, Christoph Sterz, Yanina Yurchenko, Patrick Baudisch

Hasso Plattner Institute, Potsdam, Germany {first.last}@hpi.uni-potsdam.de

[1]Hasselt University, iMinds Diepenbeek, Belgium raf.ramakers@uhasselt.be

[2]University of Copenhagen, Copenhagen, Denmark esbenwp@diku.dk

Figure 1: This example of a museum exhibit on basic molecules allows visitors to interact by kicking physical objects around—which we call *kickables*. (a) This visitor starts a tutorial video by pushing a kickable from pause to play. (b) Another visitor scrubs through a different video. (c) This visitor assembles a water molecule by moving a red hydrogen atom towards a blue oxygen atom.

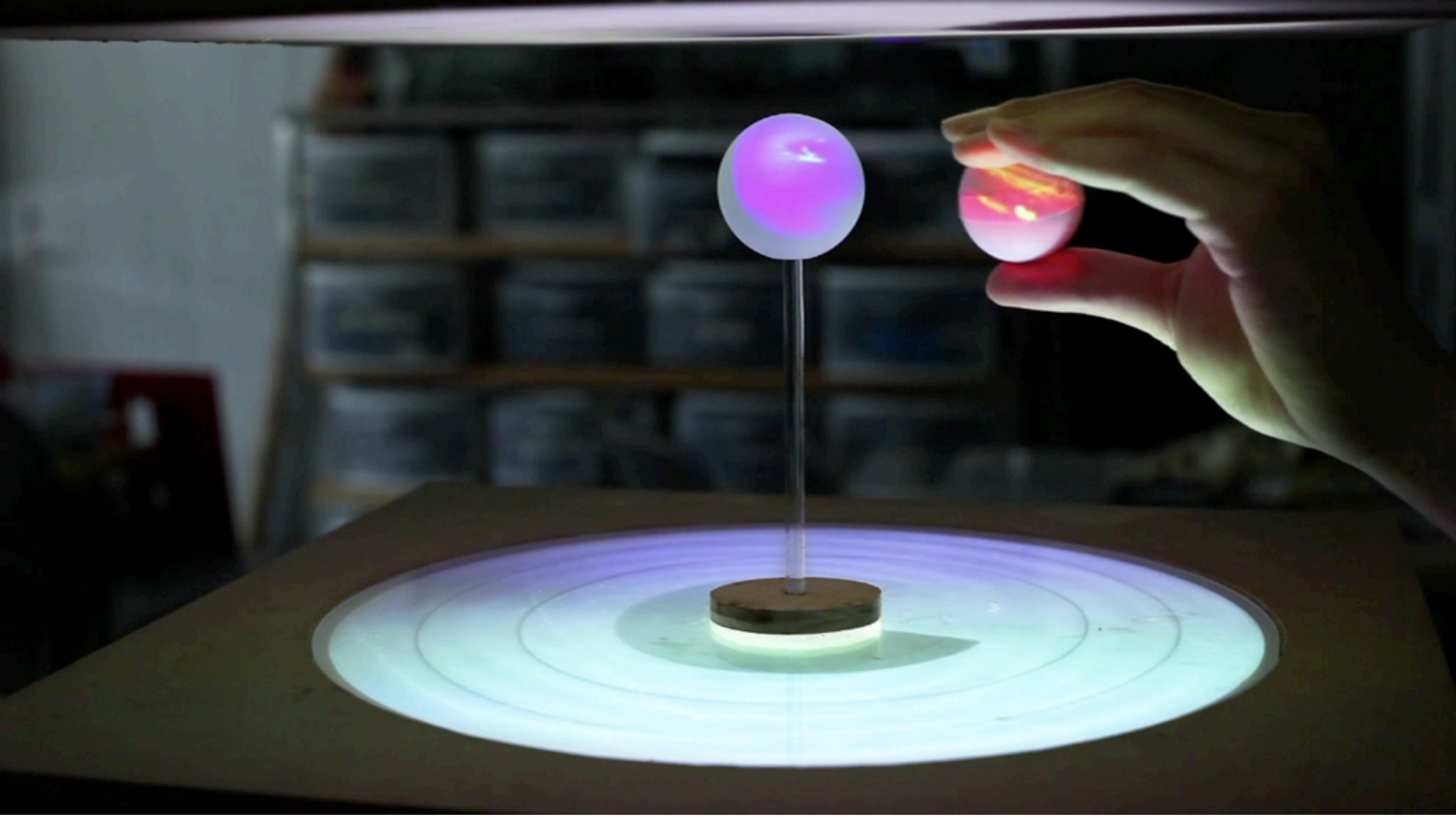
ABSTRACT

We introduce the concept of tangibles that users manipulate with their feet. We call them *kickables*. Unlike traditional tangibles, kickables allow for very large interaction surfaces as kickables reside on the ground. The main benefit of kickables over other foot-based modalities (e.g., foot touch), is their strong affordance, which we validate in two user studies. This affordance makes kickables well-suited for walk-up installations, such as tradeshows or museum exhibits.

We present a custom design as well as five sets of standard kickables to help application designers create kickable applications faster. Each set supports multiple standard controls, such as push buttons, switches, dials, and sliders. In doing so, each set explores a different design principle, in particular different mechanical constraints. We demon-

On the flipside, tabletops only accommodate a few users at a time (e.g., two to eight [27]), as the size of the interaction surface is limited by users' arm length [3]. This prevents tabletops from scaling to the dozens or hundreds of visitors that museums and tradeshow exhibits tend to attract. The limited size of the interaction surface also limits tabletops to display objects that fit on a table. Thus, for instance, no life-size cars, dinosaur skeletons, or large multi-user interaction spaces, such as the chemistry simulation in Figure 1c.

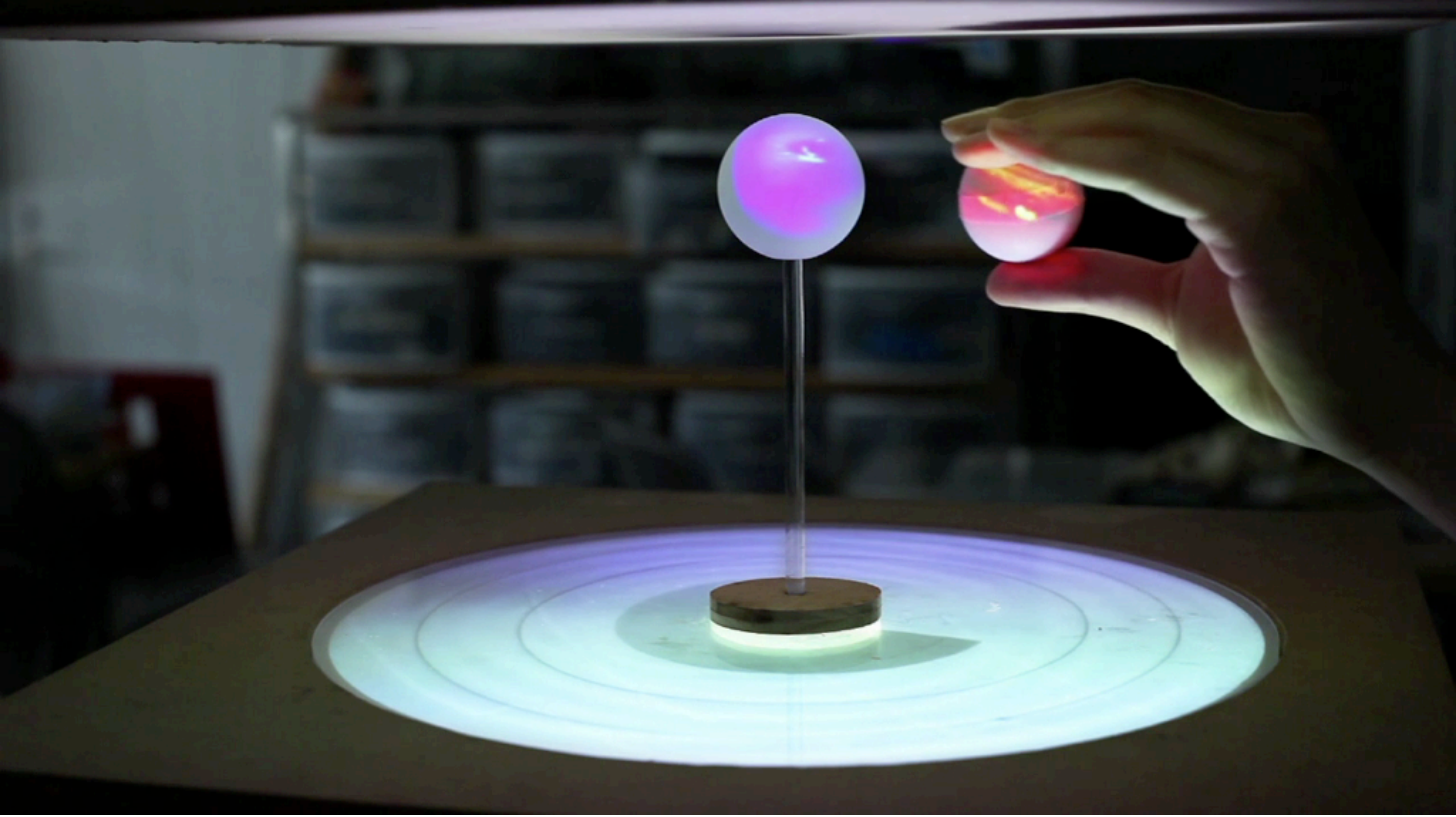
In order to accommodate dozens or hundreds of visitors at a time, researchers have proposed interactive floors (e.g., iGameFloor [12] or Multitoe [3]). For instance, the Epidemik [36] exposition in Paris' Cité des Sciences museum used 37 ceiling mounted projectors and 31 cameras for tracking to create a 450 m² seamless interactive floor, al-



is this a tangible UI?

<30s brainstorming>

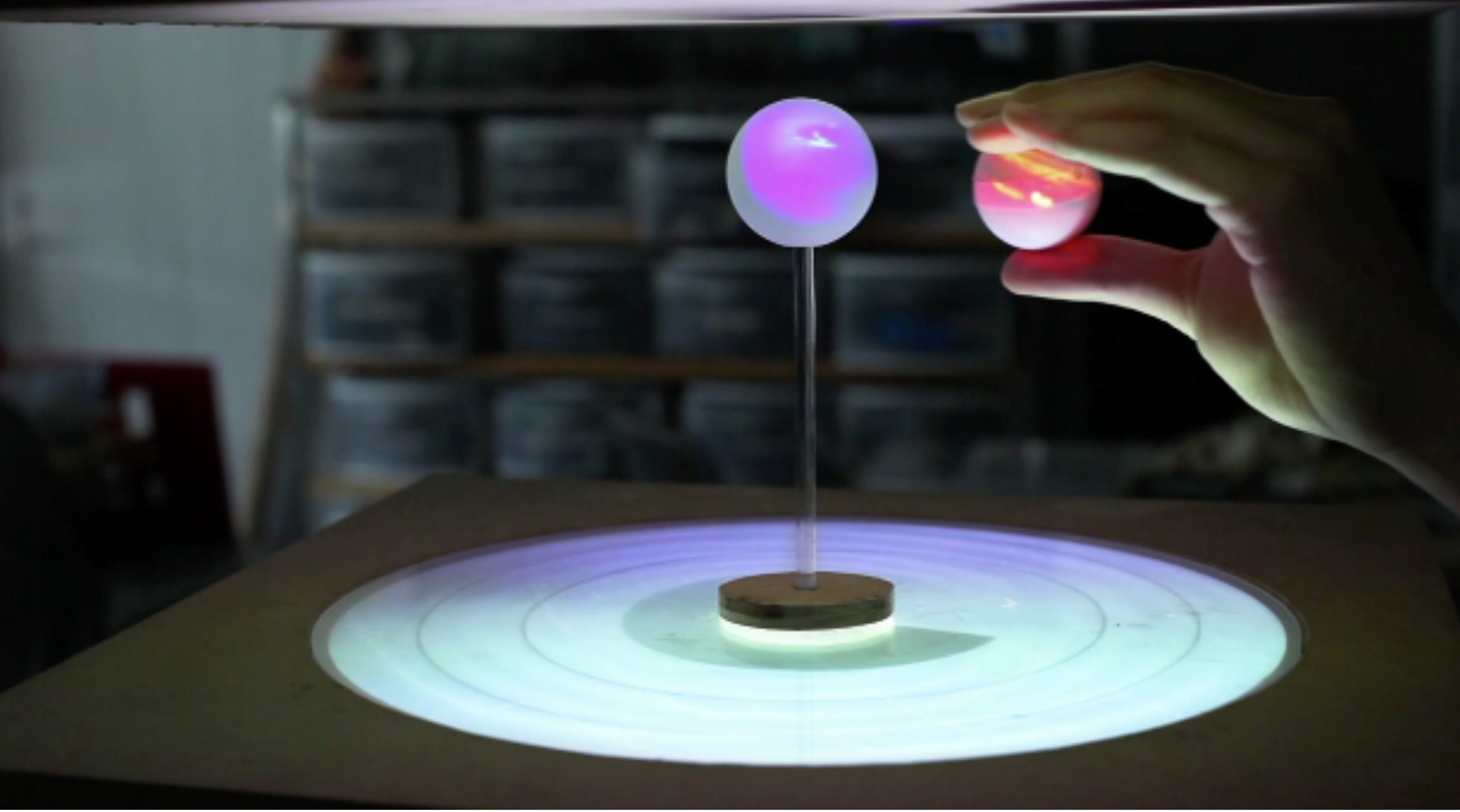
[ZeroN, 2012]



is this a tangible UI?

<30s brainstorming>

[ZeroN, 2012]



is this a tangible UI?

yes, sphere represents a planet or the sun

[ZeroN, 2012]

ZeroN: Mid-Air Tangible Interaction Enabled by Computer Controlled Magnetic Levitation

Jinha Lee[1], Rehmi Post[2], Hiroshi Ishii[1]

[1]MIT Media Laboratory
75 Amherst St.
Cambridge, MA, 02139
{jinhalee, ishii}@media.mit.edu

[2]MIT Center for Bits and Atoms
20 Ames St.
Cambridge, MA, 02139
rehmi.post@cba.mit.edu

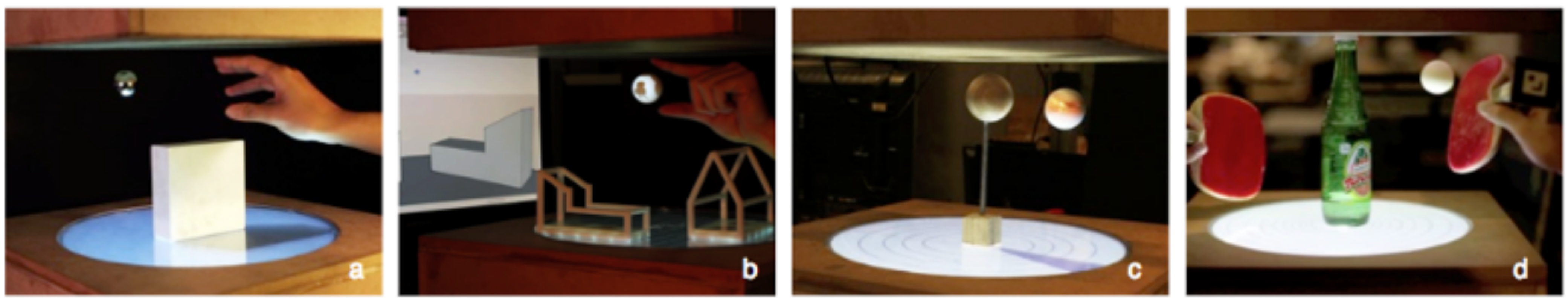


Figure 1. What if users could take a physical object off the surface and place it in the air? ZeroN enables such mid-air tangible interaction with computer controlled magnetic levitation. Various 3D applications can be redesigned with this interaction modality: a),b) architectural simulation, c) physics simulation, d) entertainment: tangible 3D pong-game.

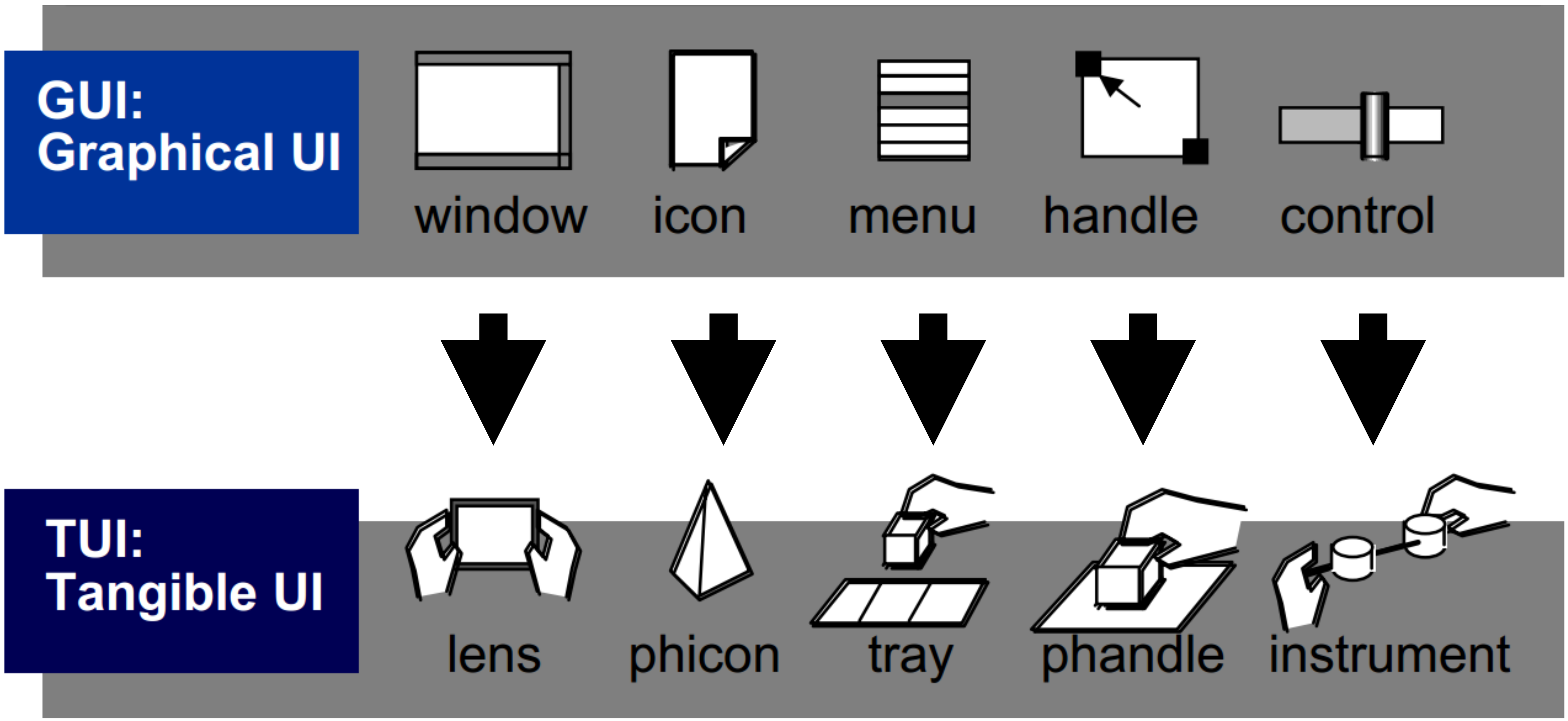
ABSTRACT

This paper presents ZeroN, a new tangible interface element that can be levitated and moved freely by computer in a three dimensional space. ZeroN serves as a tangible representation of a 3D coordinate of the virtual world through which users can see, feel, and control computation. To accomplish this we developed a magnetic control system that can levitate and actuate a permanent magnet in a predefined 3D volume. This is combined with an optical tracking and display system that projects images on the levitating object. We present applications that explore this new interaction modality. Users are invited to place or move the ZeroN object just as they can place objects on surfaces. For example, users can place the sun above physical objects to cast digital shadows, or place a planet that will start revolv-

INTRODUCTION

Tangible interfaces attempt to bridge the gap between virtual and physical spaces by embodying the digital in the physical world [7]. Tabletop tangible interfaces have demonstrated a wide range of interaction possibilities and utilities. Despite their compelling qualities, tabletop tangible interfaces share a common constraint. Interaction with physical objects is inherently constrained to 2D planar surfaces due to gravity. This limitation might not appear to be a constraint for many tabletop interfaces, when content is mapped to surface components, but we argue that there are exciting possibilities enabled by supporting true 3D manipulation. There has been some movement in this direction already; researchers are starting to explore interactions with three-dimensional content using space above the tabletop

1997: Hiroshi Ishii, Tangible UI classification



metaDESK [Ullmer UIST'97]

1997: metaDesk

metaDESK [Ullmer UIST'97]

The metaDESK: Models and Prototypes for Tangible User Interfaces

Brygg Ullmer and Hiroshi Ishii
MIT Media Lab
Tangible Media Group
20 Ames St., E15-445
Cambridge, MA 02139 USA
+1 617 253 4121
{ullmer, ishii}@media.mit.edu

ABSTRACT
The metaDESK is a user interface platform demonstrating new interaction techniques we call "tangible user interfaces." We explore the physical instantiation of interface elements from the graphical user interface paradigm, giving physical form to windows, icons, handles, menus, and controls. The design and implementation of the metaDESK display, sensor, and software architectures is discussed. A prototype application driving an interaction with geographical space, Tangible Geospace, is presented to demonstrate these concepts.

Keywords: tangible user interfaces, input devices, haptic input, augmented reality, ubiquitous computing

INTRODUCTION
The graphical user interface (GUI) has proven both a successful and durable model for human-computer interaction which has dominated the last decade of interface design. At the same time, the GUI approach falls short in many respects, particularly in embracing the rich interface modalities between people and the physical environments they inhabit. Systems exploring augmented reality and ubiquitous computing have begun to address this challenge. However, these efforts have often taken the form of exporting the GUI paradigm to more world-situated devices, falling short of much of the richness of physical-space

the metaDESK along with two companion platforms, the transBOARD and ambientROOM. Together, these platforms explore both graspable physical objects and ambient environmental displays as means for seamlessly coupling people, digital information, and the physical environment.

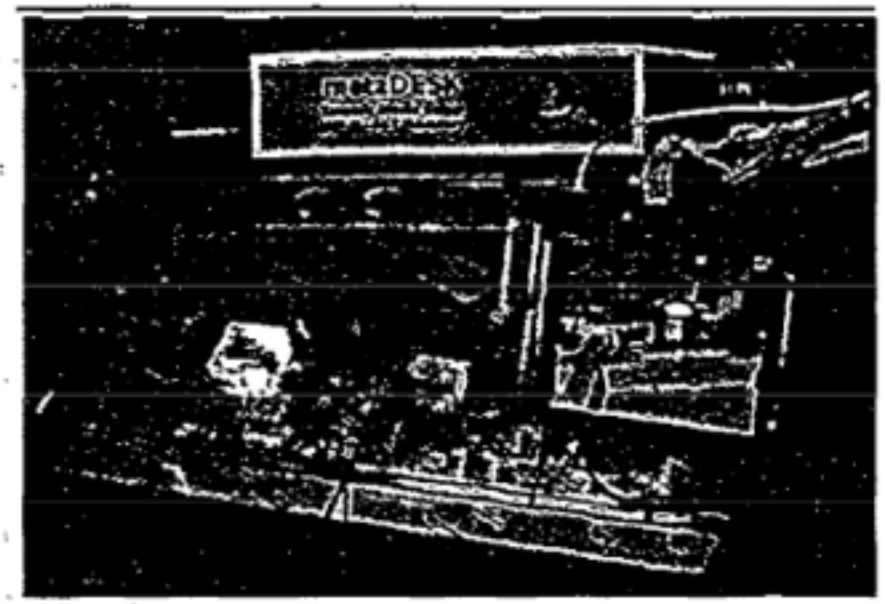


Figure 1: The metaDESK system overview

The metaDESK system, shown in Figure 1, consists of several components: the *desk*, a nearly-horizontal back-projected graphical surface; the *active lens*, an arm-mounted flat-panel display; the *passive lens*, an optically transparent surface through which the desk projects; and an assortment of physical objects and instruments which are used on desk's surface. These components are sensed by an array of

why tangible?

world with **objects, tools, toys, and people.**

but we stare at a single glowing screen
attached to an array of buttons and a **mouse.**

how your computer sees you:

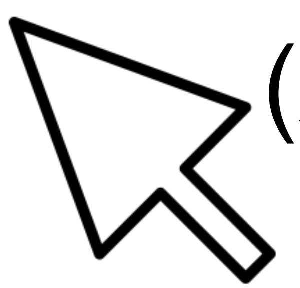
(x,y)

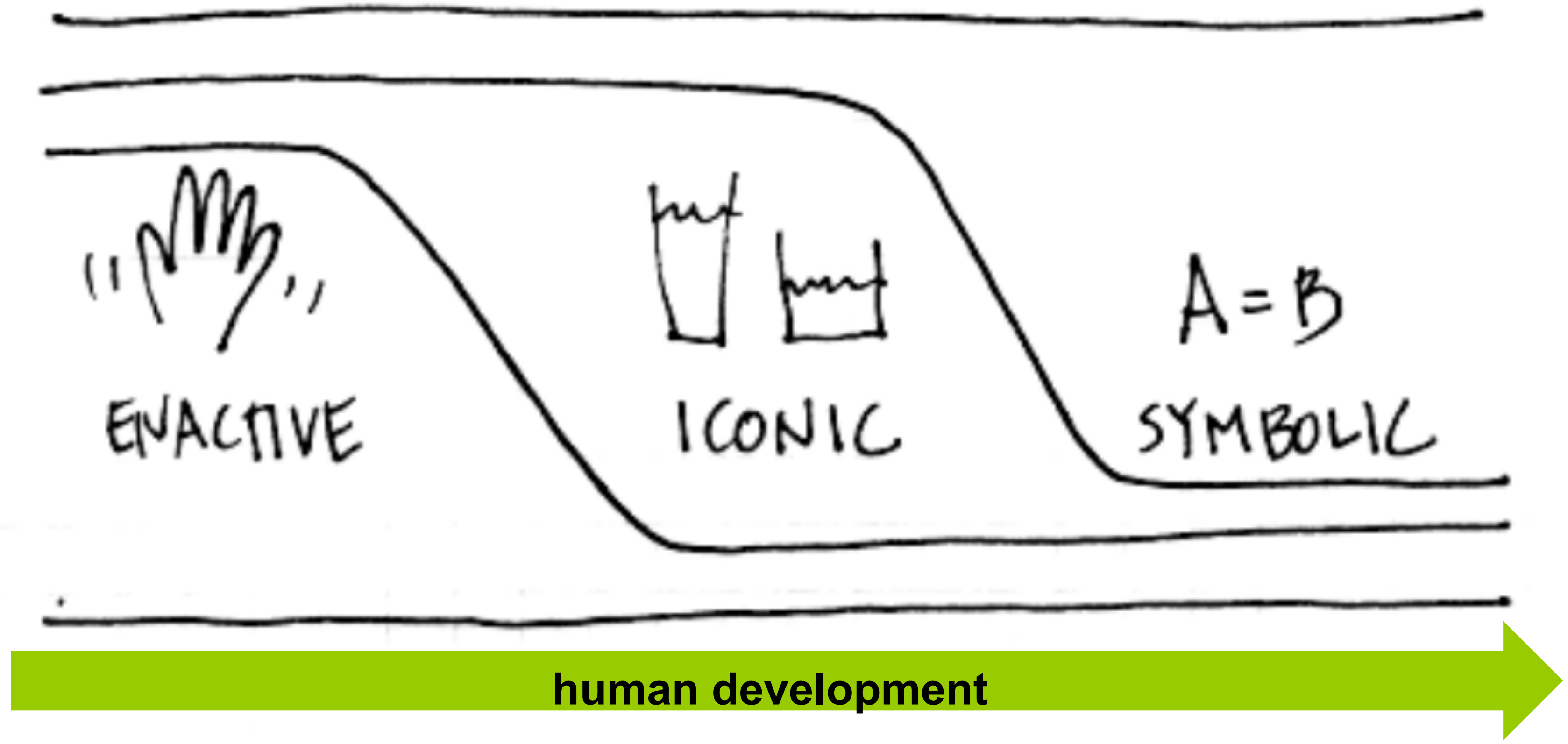
-> very **limited bandwidth** for interaction

[Fitzmaurice CHI'95]

Tangible UI:

a vision of **how human and machine** should come together

not like this  (x,y) but with full bandwidth

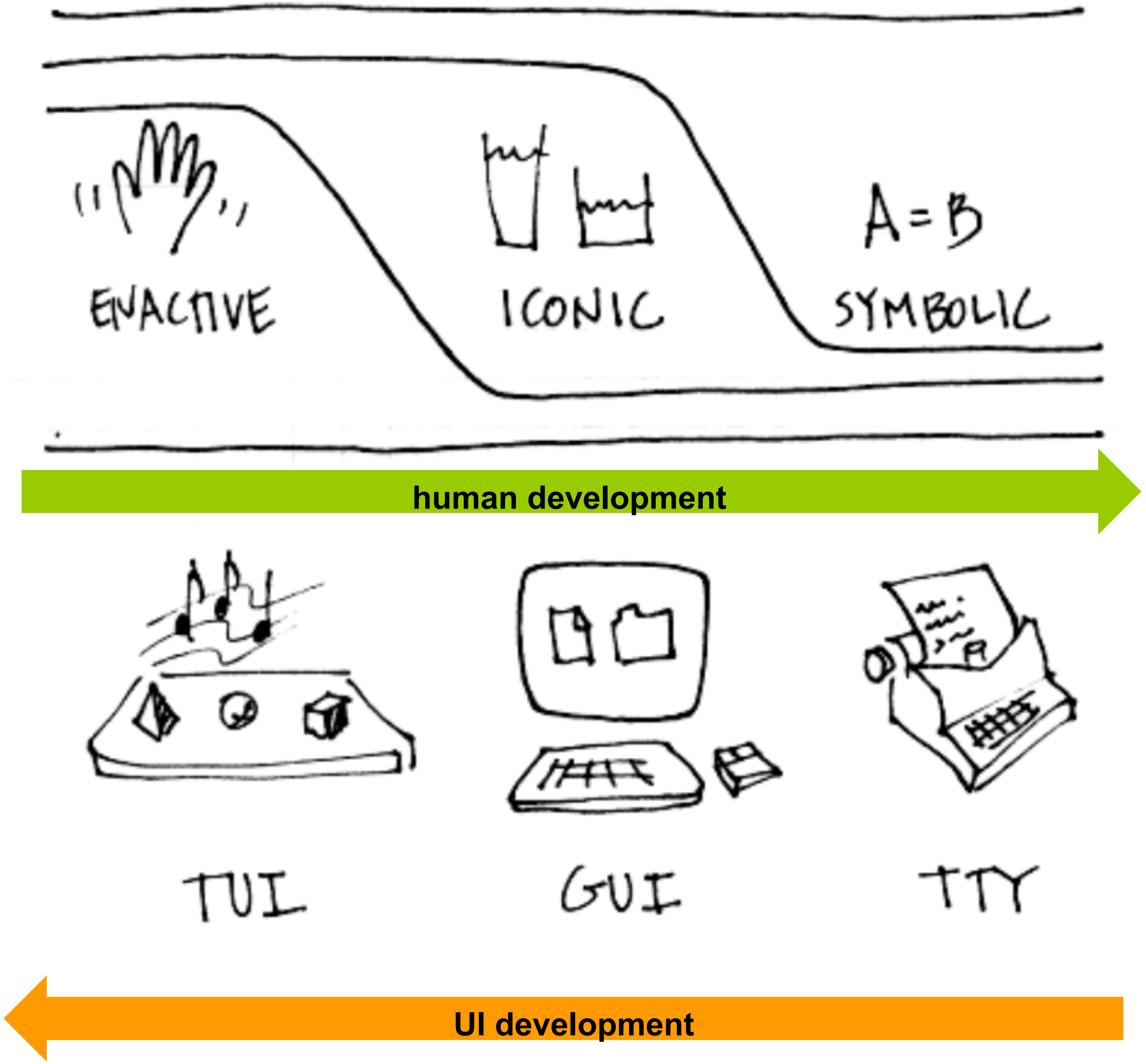


actions
representing a result

images
representing a concept

symbolic
describing the concept

Interaction Design Sketchbook [Verplank '09]

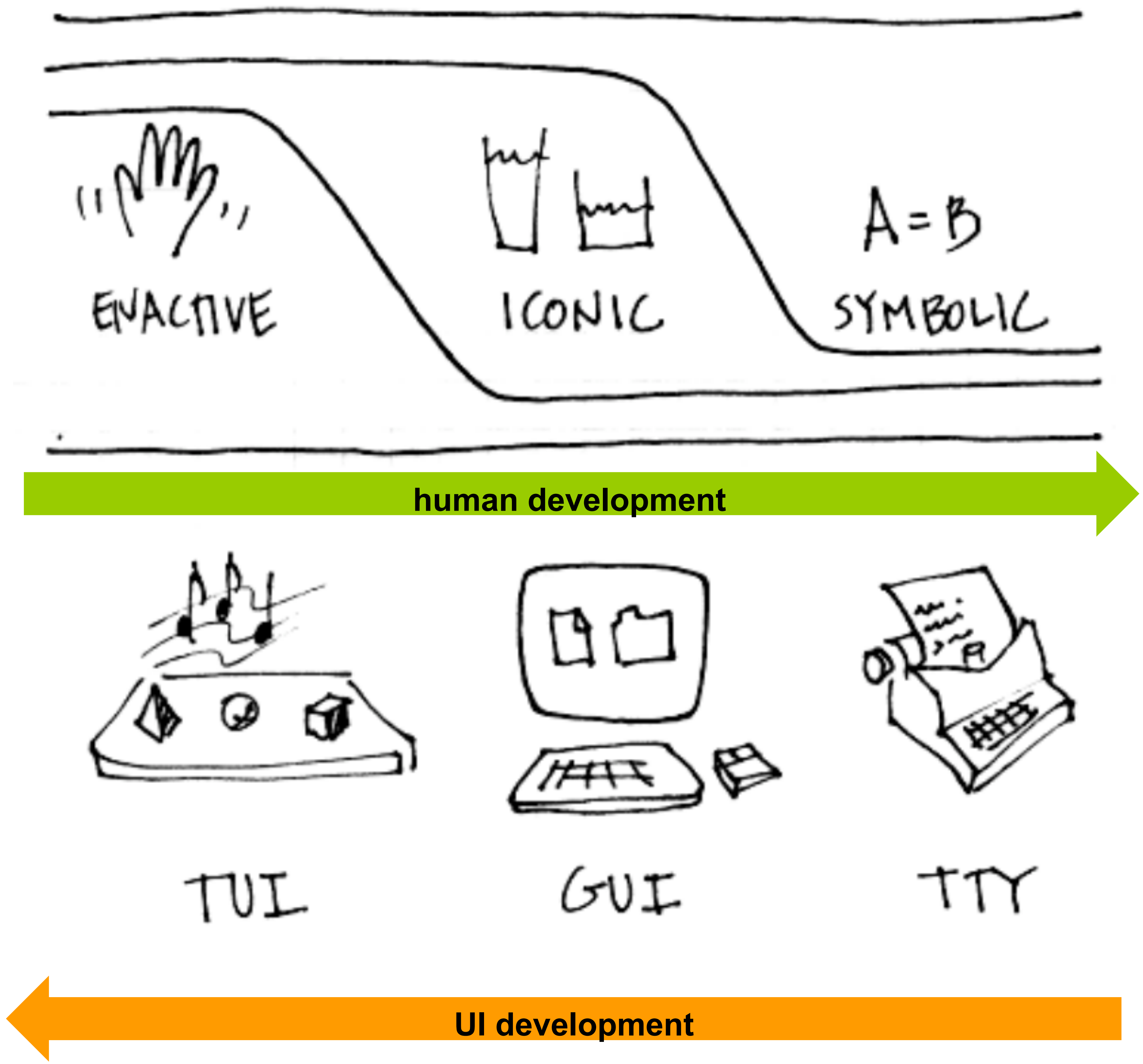


Interaction Design Sketchbook [Verplank '09]

symbolic came first: command line interfaces

iconic: today graphical user interfaces with desktop metaphor

but **control is always separate** from its (iconic) representation



Interaction Design Sketchbook [Verplank '09]

connecting bits with atoms

Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms

Hiroshi Ishii and Brygg Ullmer
MIT Media Laboratory
Tangible Media Group
20 Ames Street, Cambridge, MA 02139-4307 USA
{ishii, ullmer}@media.mit.edu

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BITS & ATOMS
We live between two realms: our physical environment and cyberspace. Despite our dual citizenship, the absence of seamless couplings between these parallel existences leaves a great divide between the worlds of bits and atoms. At the present, we are torn between these parallel but disjoint spaces.

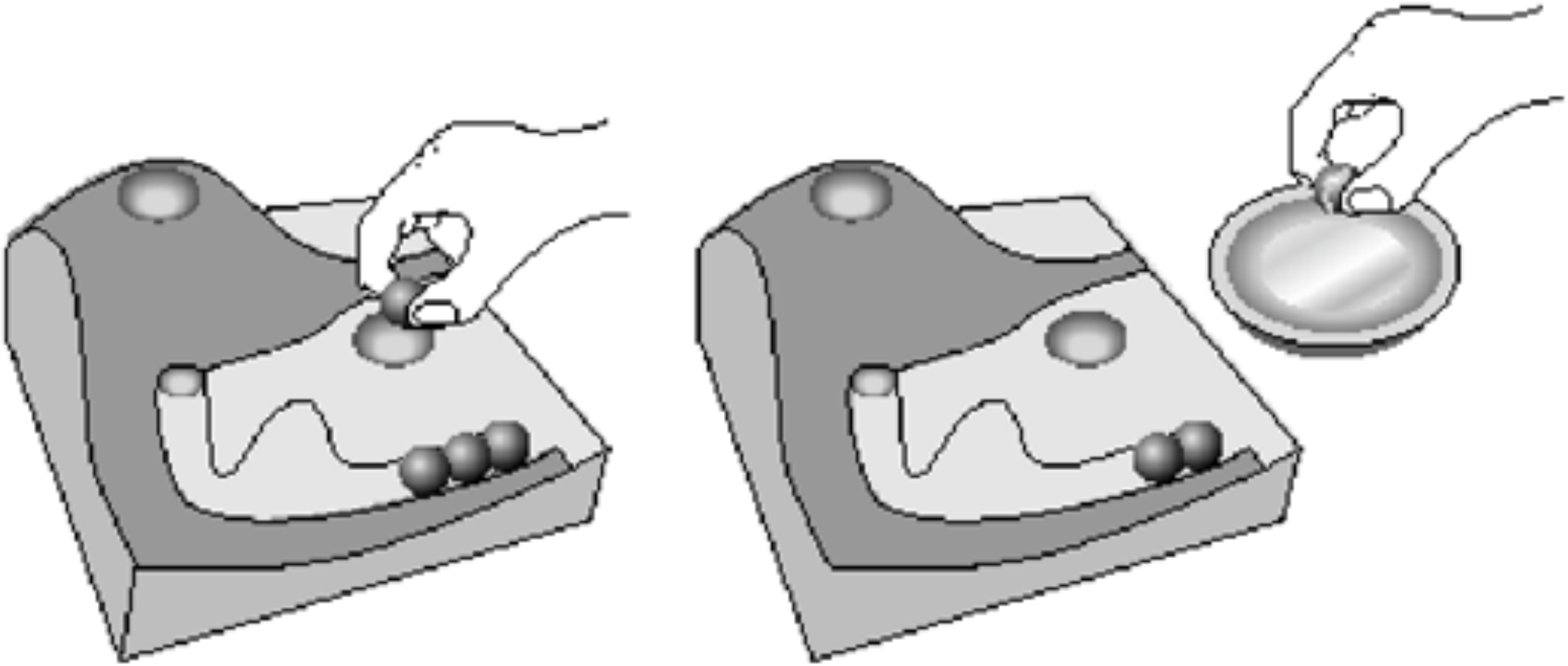
Figure 1 Sketches made at Collection of Historical Scientific Instruments at Harvard University

We are now almost constantly "wired" so that we can be here (physical space) and there (cyberspace) simultaneously [14]. Streams of bits leak out of cyberspace through a myriad of rectangular screens into the physical world as photon beams. However, the interactions between people and cyberspace are now largely confined to traditional GUI (Graphical User Interface)-based boxes sitting on desktops or laptops. The interactions with these GUIs are separated from the ordinary physical environment within which we live and interact.

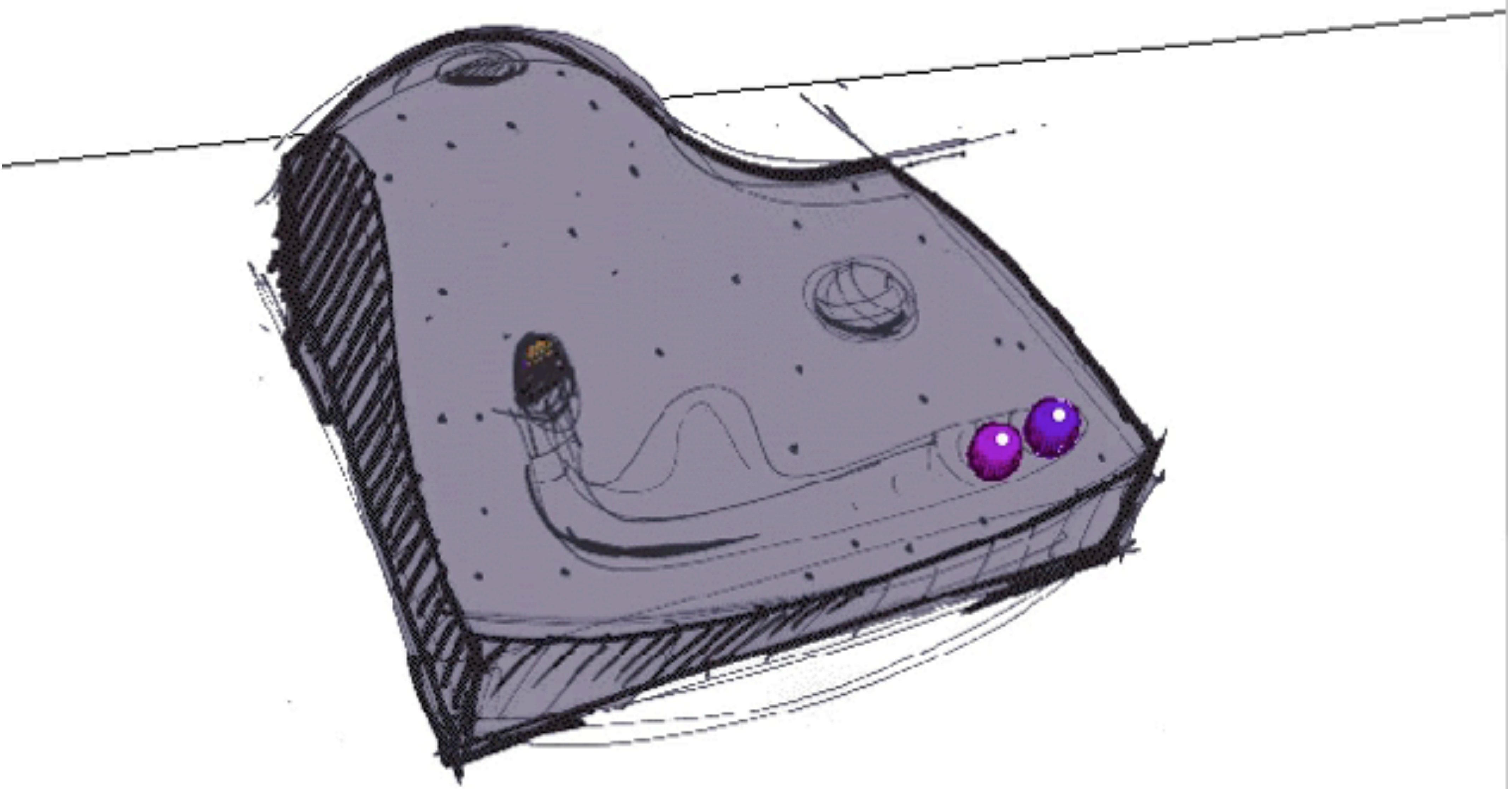
Although we have developed various skills and work practices for processing information through haptic interactions with physical objects (e.g., scribbling messages on Post-It™ notes and spatially manipulating them on a wall) as well as peripheral senses (e.g., being

properties of
good tangible UI

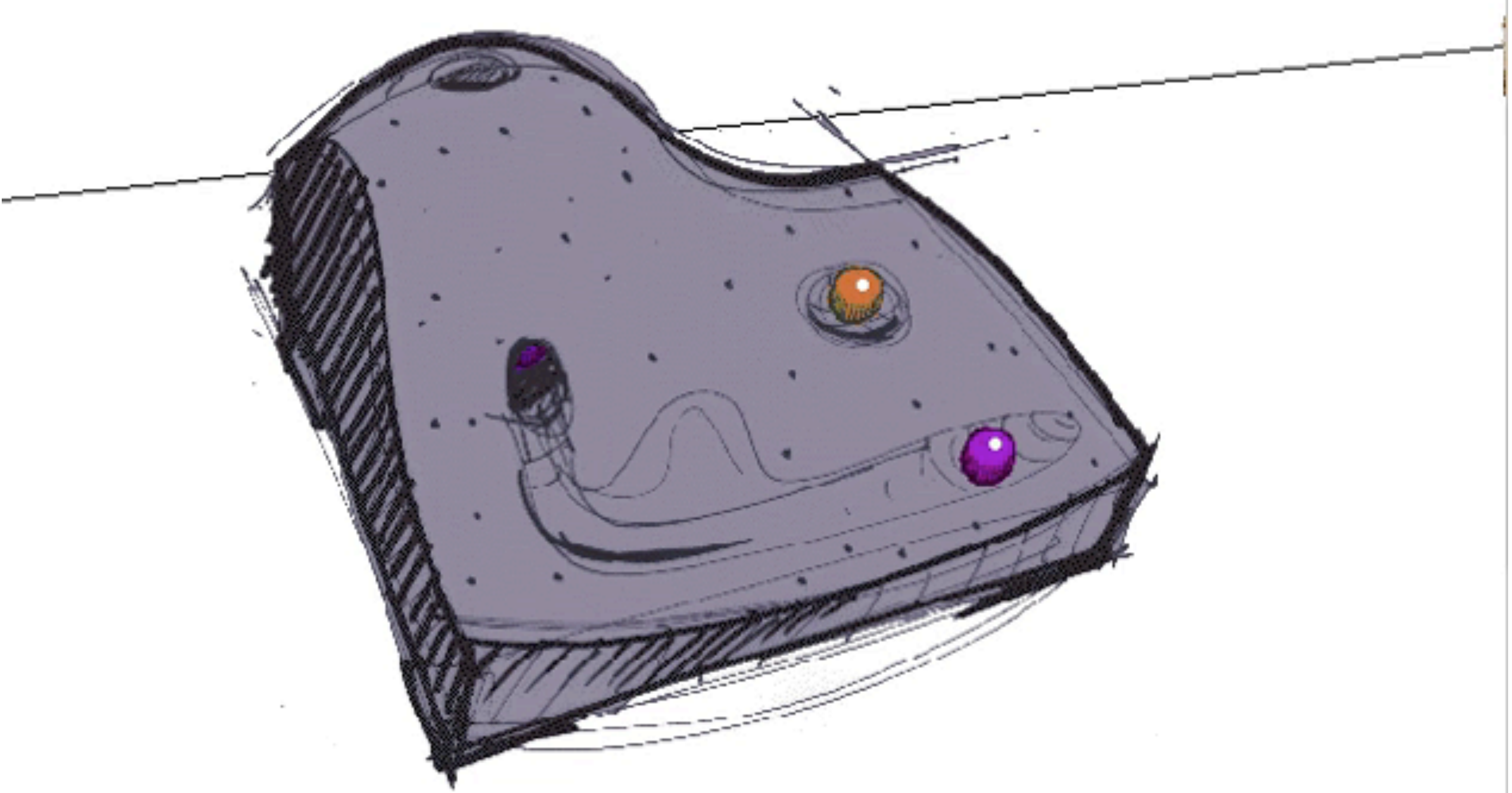
let’s look at **two examples**
that have a lot in common…



1992: Durrell Bishop marble answering machine



1992: Durrell Bishop marble answering machine



1992: Durrell Bishop marble answering machine

2001: Hiroshi Ishii Music Bottles

bottles [Ishii,CHI'01]

are these **good tangible UI?**

if **yes, why?**
if **no, why not?**

<30s brainstorming>

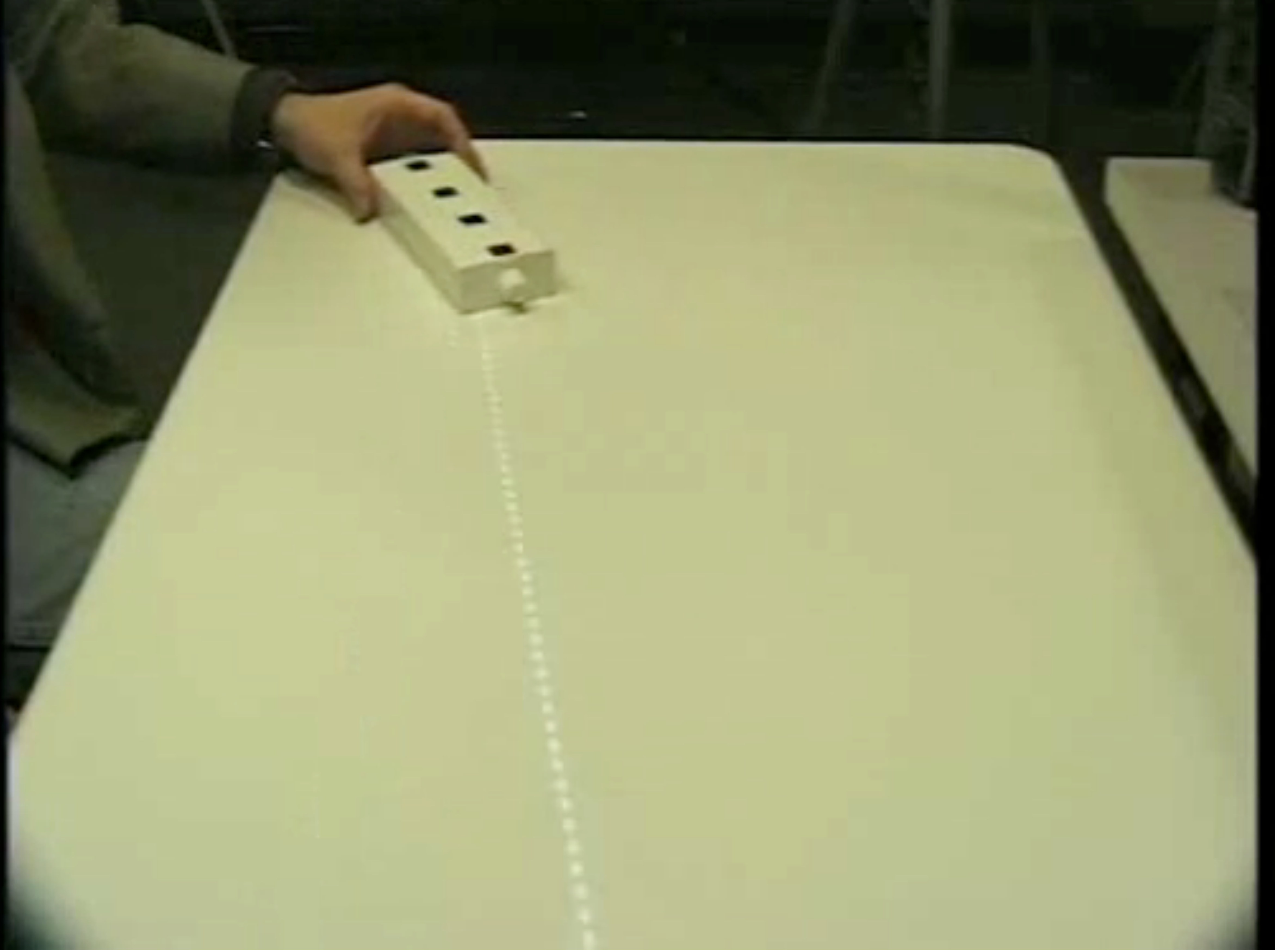
mapping should be avoided:

- bottles typically don’t contain music…
- voices are typically not contained in marbles…

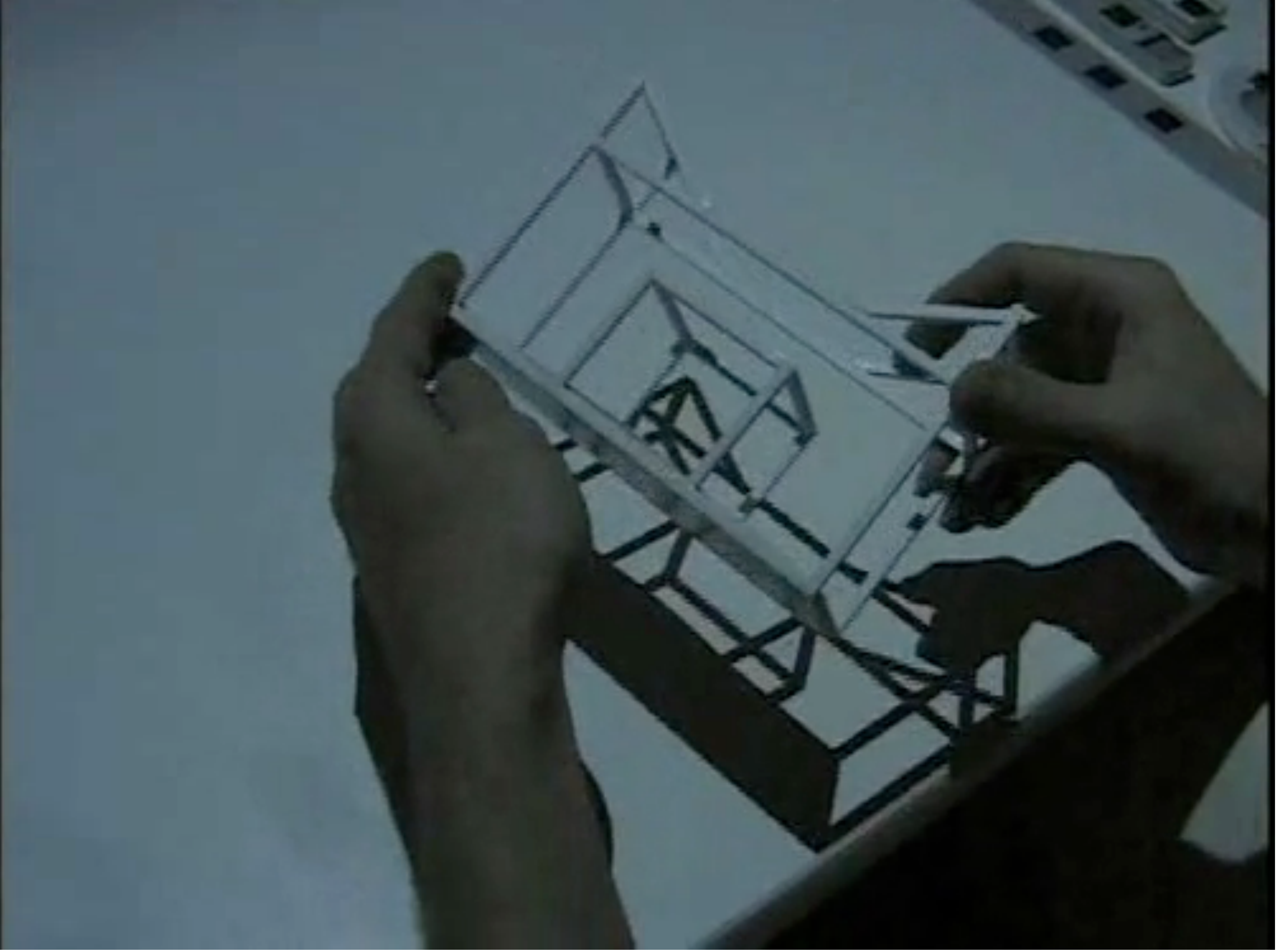
- **users need to learn the metaphor**
- if the thing you are trying to represent is **non-tangible** (e.g., music), mapping to a physical object doesn’t work

i/o brush[Ryokai,CHI'04]

- much better, here the **mapping disappears.**
- tangibles and what they represent are almost the same
- large benefit from **feeling the 'real' constraints**



1999: John Underkoffler: urban planning and design desk



1999: John Underkoffler: urban planning and design desk

Urp: A Luminous-Tangible Workbench for Urban Planning and Design

John Underkoffler and Hiroshi Ishii
MIT Media Laboratory, Tangible Media Group
Cambridge, MA
{jh,ishii}@media.mit.edu

ABSTRACT

We introduce a system for urban planning – called *Urp* – that integrates functions addressing a broad range of the field's concerns into a single, physically based workbench setting. The I/O *Bulb* infrastructure on which the application is based allows physical architectural models placed on an ordinary table surface to cast shadows accurate for arbitrary times of day; to throw reflections off glass facade surfaces; to affect a real-time and visually coincident simulation of pedestrian-level windflow; and so on.

We then use comparisons among *Urp* and several earlier *I/O Bulb* applications as the basis for an understanding of *luminous-tangible interactions,* which result whenever an interface distributes meaning and functionality between physical objects and visual information projectively coupled to those objects. Finally, we briefly discuss two issues common to all such systems, offering them as informal thought-tools for the design and analysis of luminous-tangible interfaces.

Keywords

urban design, urban planning, architectural simulation, luminous-tangible interface, direct manipulation, augmented reality, prototyping tool, interactive projection, tangible bits

SCENARIO

Two urban planners, charged with the design of a new plaza, unroll onto a large table a map showing the portion of the city that will contain their project. They place an architectural model of one of the site's buildings onto the map. Immediately a long shadow appears, registered precisely to the base of the model, and tracks along with it as it

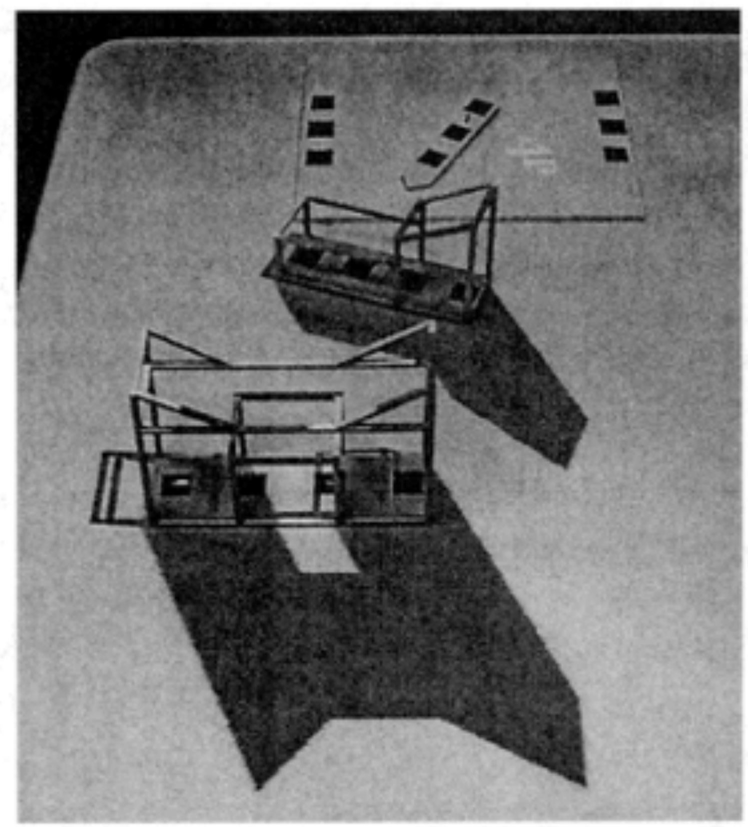
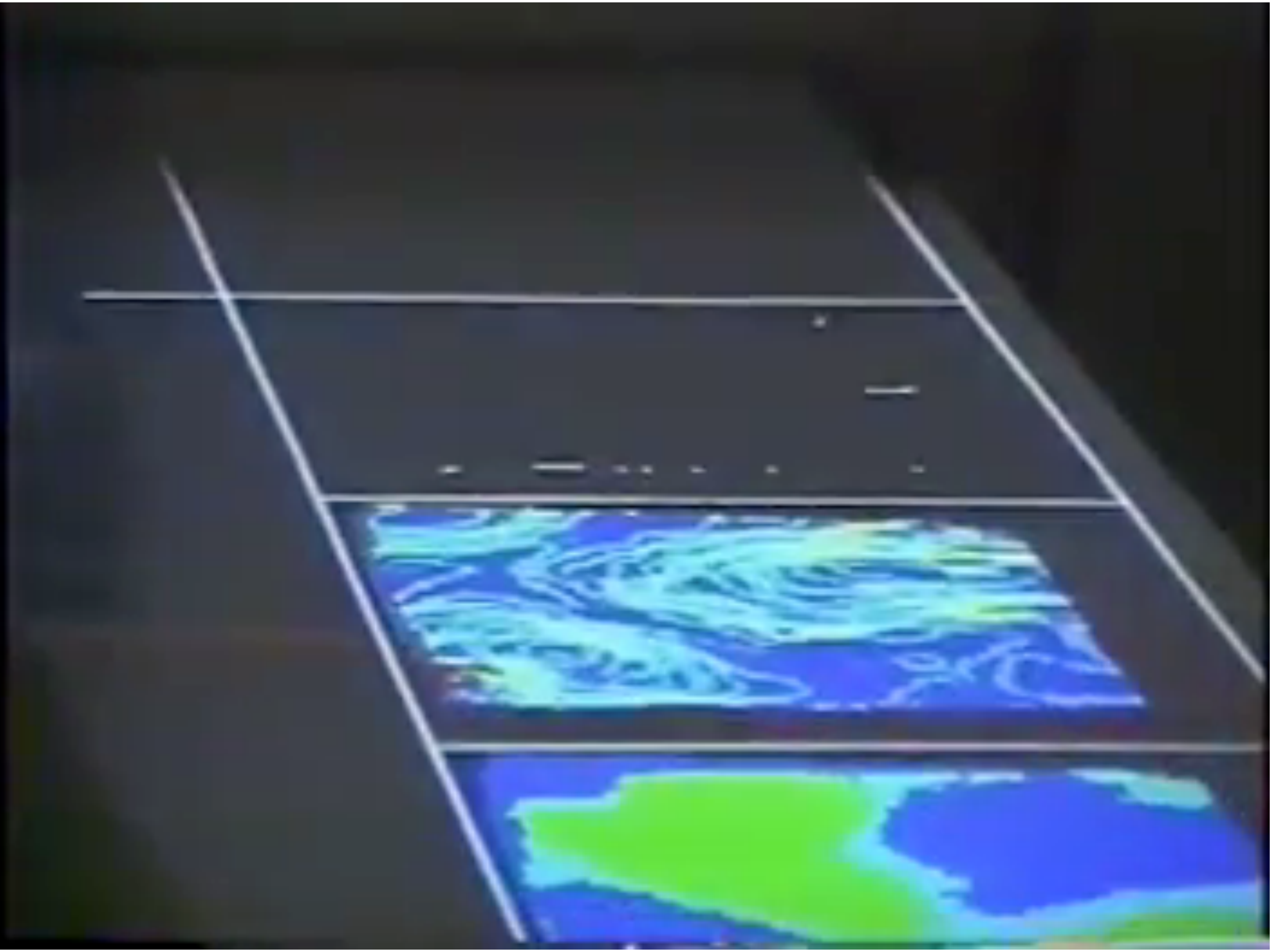


FIGURE 1: URP, SHOWING LATE-AFTERNOON SHADOWS

twenty yards to the north of an east-west highway that borders the plaza on the south; one of the planners places a long road-like strip of plastic on top of the map's representation of the highway, and tiny projected cars begin progressing at various speeds along its four lanes. The other planner brings a wand into contact with the nearby building, and the model's facade, now transformed to glass, throws a bright reflection onto the ground in addition to (but in the opposite direction from) its existing shadow. "We're blinding the oncoming rush-hour traffic for about ninety yards here at 7 AM," he observes. "Can we get away with a little rotation?' They rotate the building by less than



2002: Ben Piper and Hiroshi Ishii: Illuminating Clay

Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis

Ben Piper, Carlo Ratti* and Hiroshi Ishii
Tangible Media Group
MIT Media Laboratory
Cambridge, Mass. USA
{benpiper,ratti,ishii}@media.mit.edu

ABSTRACT

This paper describes a novel system for the real-time computational analysis of landscape models. Users of the system – called *Illuminating Clay* – alter the topography of a clay landscape model while the changing geometry is captured in real-time by a ceiling-mounted laser scanner. A depth image of the model serves as an input to a library of landscape analysis functions. The results of this analysis are projected back into the workspace and registered with the surfaces of the model.

We describe a scenario for which this kind of tool has been developed and we review past work that has taken a similar approach. We describe our system architecture and highlight specific technical issues in its implementation.

We conclude with a discussion of the benefits of the system in combining the tangible immediacy of physical models with the dynamic capabilities of computational simulations.

Keywords

Tangible user interface, 3D laser scanner, landscape design, physical models, GIS, DEM

SCENARIO

A group of road builders, environmental engineers and landscape designers stand at an ordinary table on which is placed a clay model of a particular site in the landscape. Their task is to design the course of a new roadway,

Figure 1. Illuminating Clay in use.
(This figure is reproduced in color on page 000.)

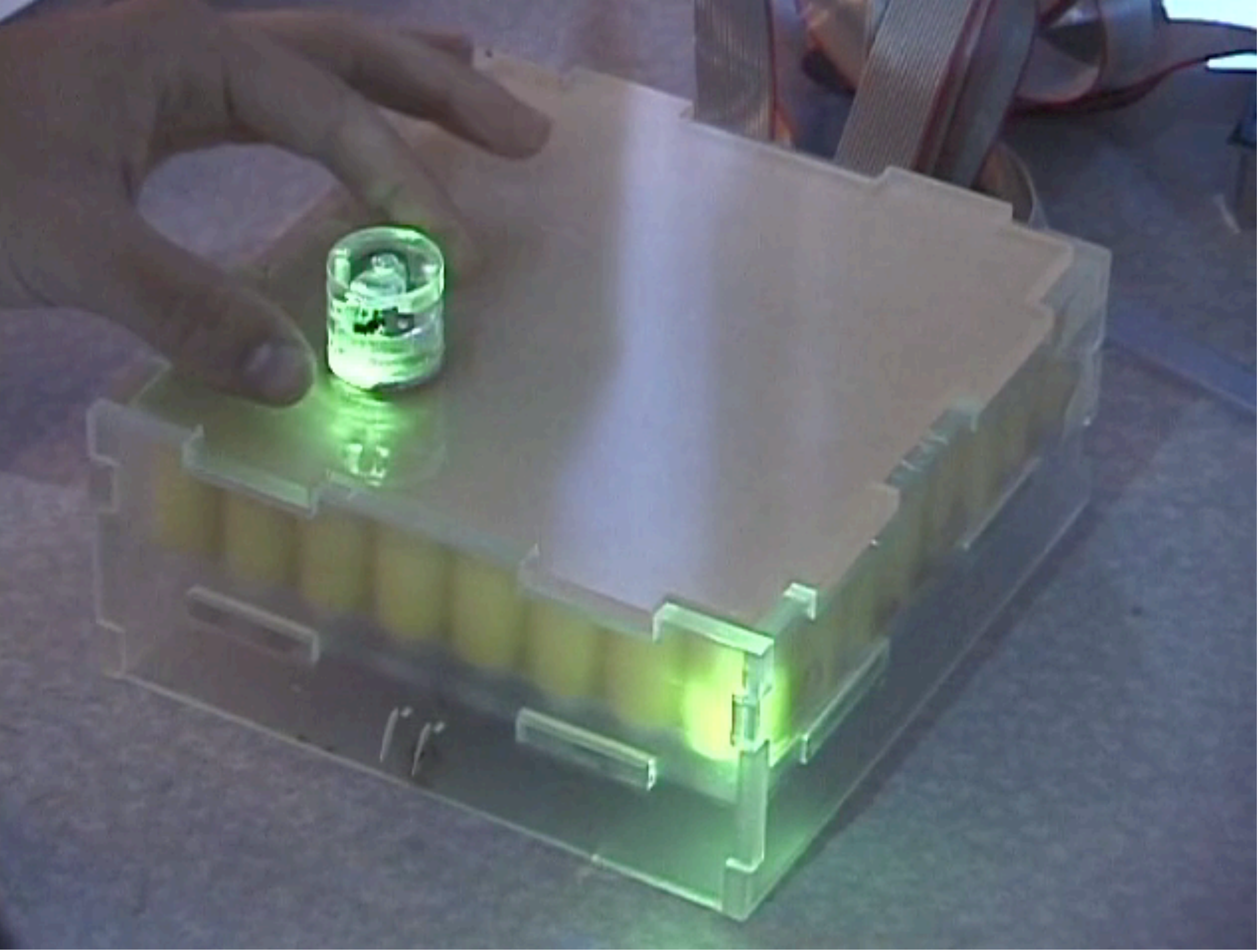
The scenario described above is one example of how the *Illuminating Clay* platform can be used to simulate dynamic forces by projecting computational representations directly into the model landscape (figure 1.).

APPLICATION DOMAIN: LANDSCAPE ANALYSIS

Developments in high-resolution commercial satellite photography, high-altitude airborne sensors, global positioning systems, digital image processing, database

closing the loop::

- the user can provide input
- the system can respond
- also allows to correct for inconsistencies



2002: Pangaro: Actuated Workbench

The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Interfaces

Gian Pangaro, Dan Maynes-Aminzade, Hiroshi Ishii
MIT Media Lab
Massachusetts Institute of Technology NE18-5F
77 Massachusetts Avenue, Cambridge, MA 02139 USA
[pangaro, monzy, ishii]@media.mit.edu

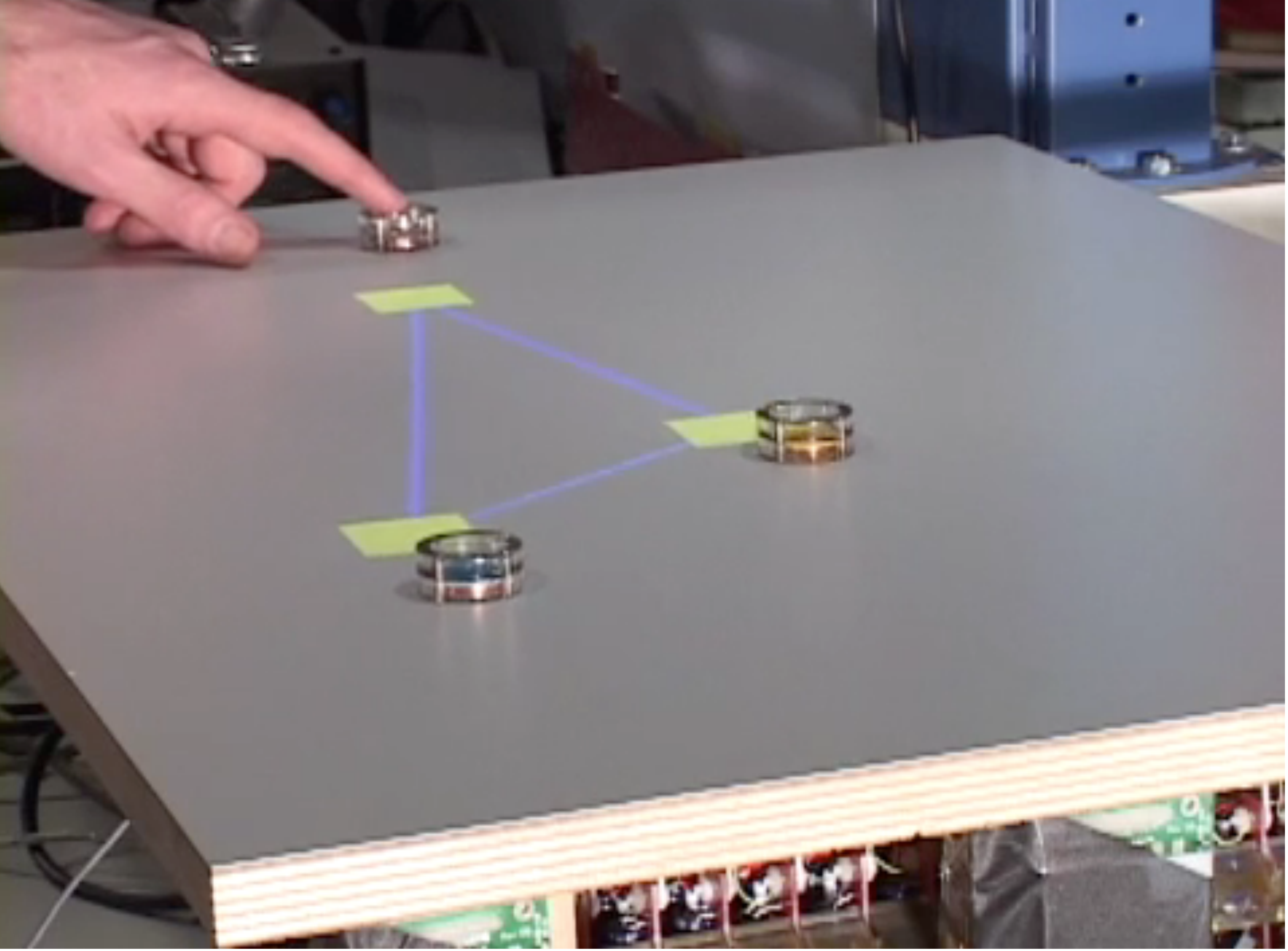
ABSTRACT
The Actuated Workbench is a device that uses magnetic forces to move objects on a table in two dimensions. It is intended for use with existing tabletop tangible interfaces, providing an additional feedback loop for computer output, and helping to resolve inconsistencies that otherwise arise from the computer's inability to move objects on the table. We describe the Actuated Workbench in detail as an enabling technology, and then propose several applications in which this technology could be useful.

KEYWORDS: Tangible user interfaces, physical interaction, actuation, synchronization, interactive surface, object tracking, computer supported cooperative work.

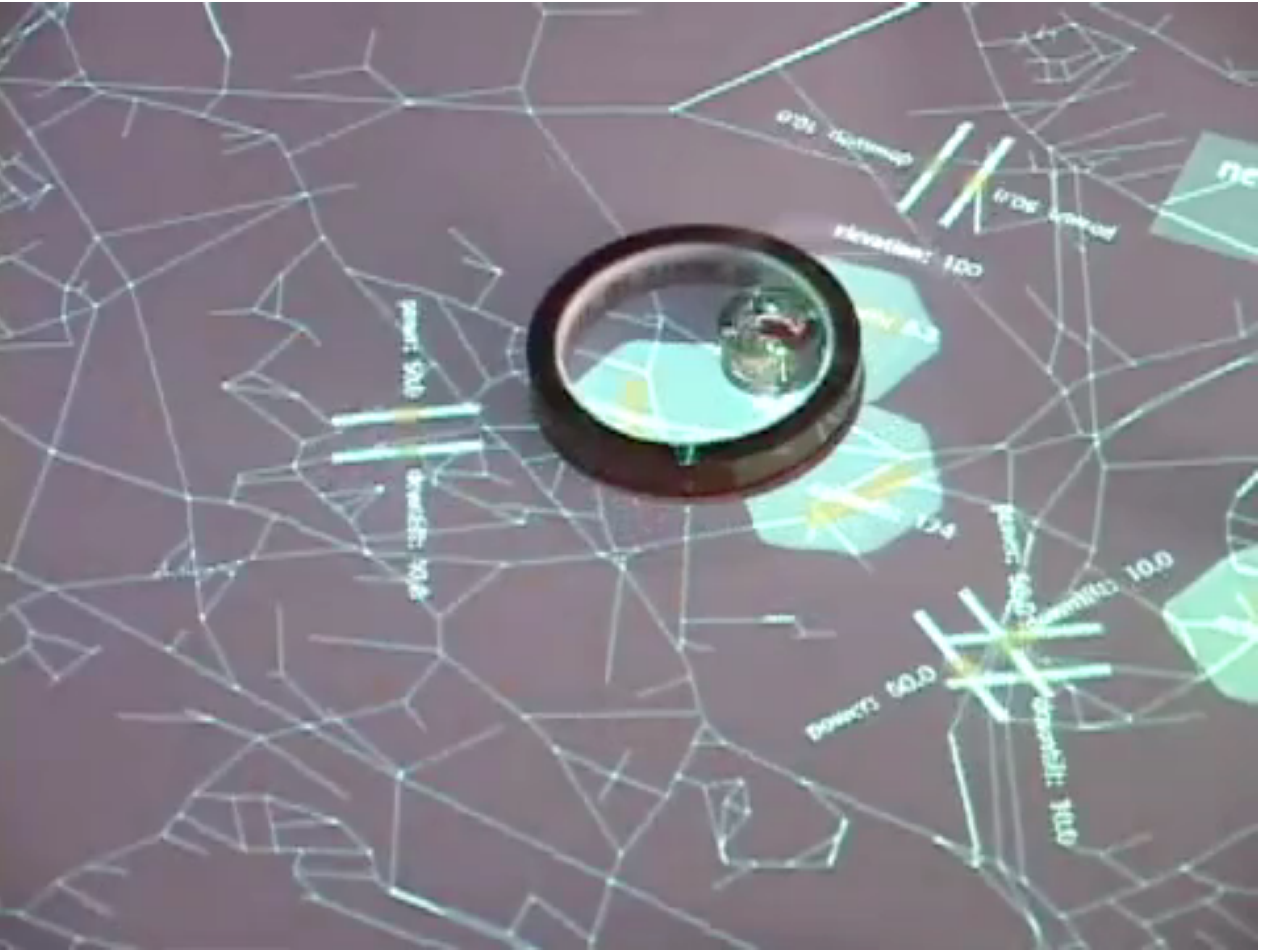
INTRODUCTION
Interactive tabletop surfaces are a promising avenue of research in Tangible User Interfaces. These systems, which we will refer to as "interactive workbenches," track the position and movement of objects on a flat surface and respond to users' physical input with graphical output. Systems such as the DigitalDesk [18], Bricks [7], Sensetable [13], and Urp [17] offer many advantages over purely graphical interfaces, including the ability for users to

Figure 1. The Actuated Workbench uses a grid of electromagnets to move a magnetic puck across a table surface.

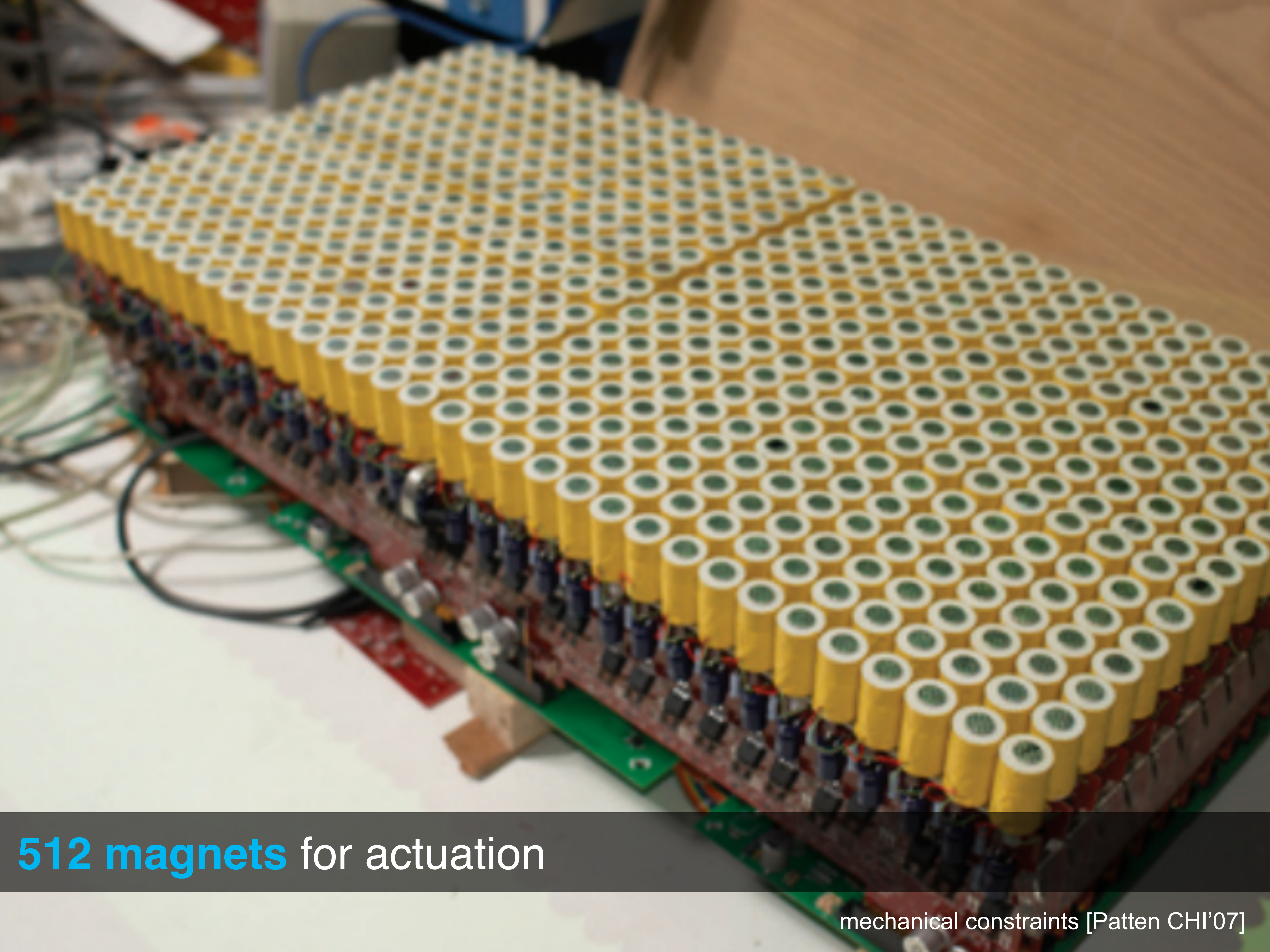
In addition, the user must sometimes compensate for inconsistencies when links between the digital data and the physical objects are broken. Such broken links can arise when a change occurs in the computer model that is not



2007: Patten: physical constraints influence computation



2007: Patten: physical constraints influence computation


512 magnets for actuation
mechanical constraints [Patten CHI'07]

Mechanical Constraints as Computational Constraints in Tabletop Tangible Interfaces

James Patten
MIT Media Lab
20 Ames St.
Cambridge, Ma . 02139
jpatten@media.mit.edu

Hiroshi Ishii
MIT Media Lab
20 Ames St.
Cambridge, Ma . 02139
ishii@media.mit.edu

ABSTRACT
This paper presents a new type of human-computer interface called Pico (Physical Intervention in Computational Optimization) based on mechanical constraints that combines some of the tactile feedback and affordances of mechanical systems with the abstract computational power of modern computers. The interface is based on a tabletop interaction surface that can sense and move small objects on top of it. The positions of these physical objects represent and control parameters inside a software application, such as a system for optimizing the configuration of radio towers in a cellular telephone network. The computer autonomously attempts to optimize the network, moving the objects on the table as it changes their corresponding parameters in software. As these objects move, the user can constrain their motion with his or her hands, or many other kinds of physical objects. The interface provides ample opportunities for improvisation by allowing the user to employ a rich variety of everyday physical objects as mechanical constraints. This approach leverages the user's mechanical intuition for how objects respond to physical forces. As well, it allows the user to balance the numerical optimization performed by the computer with other goals that are difficult to quantify. Subjects in an evaluation were more effective at solving a complex spatial layout problem using this system than with either of two alternative interfaces that did not feature actuation.

Author Keywords
tangible interfaces, physical interaction, interactive surface, improvisation, actuation.

ACM Classification Keywords

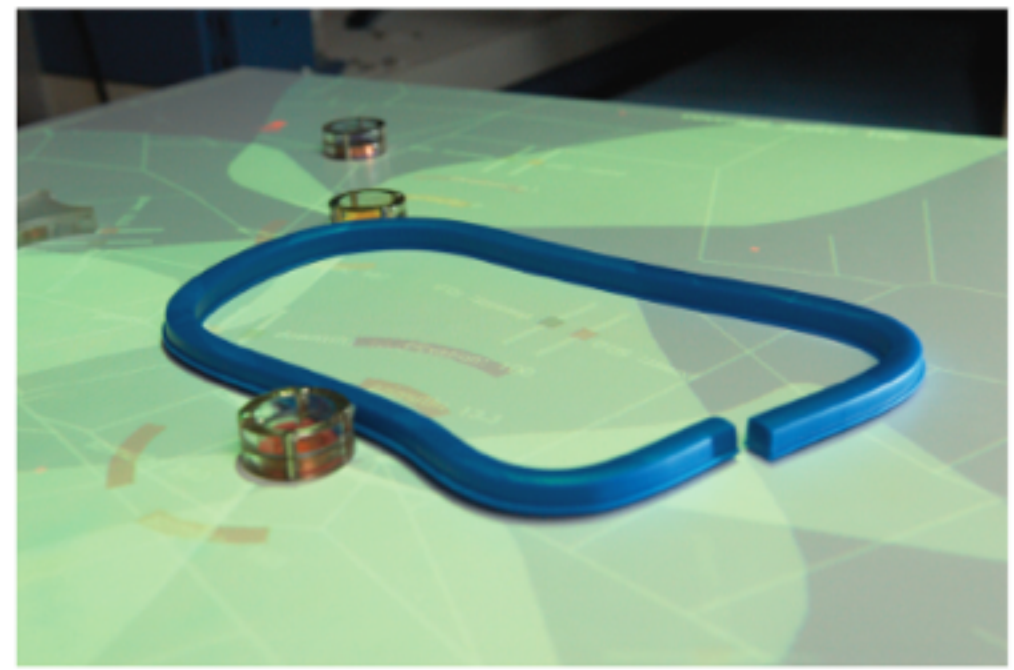


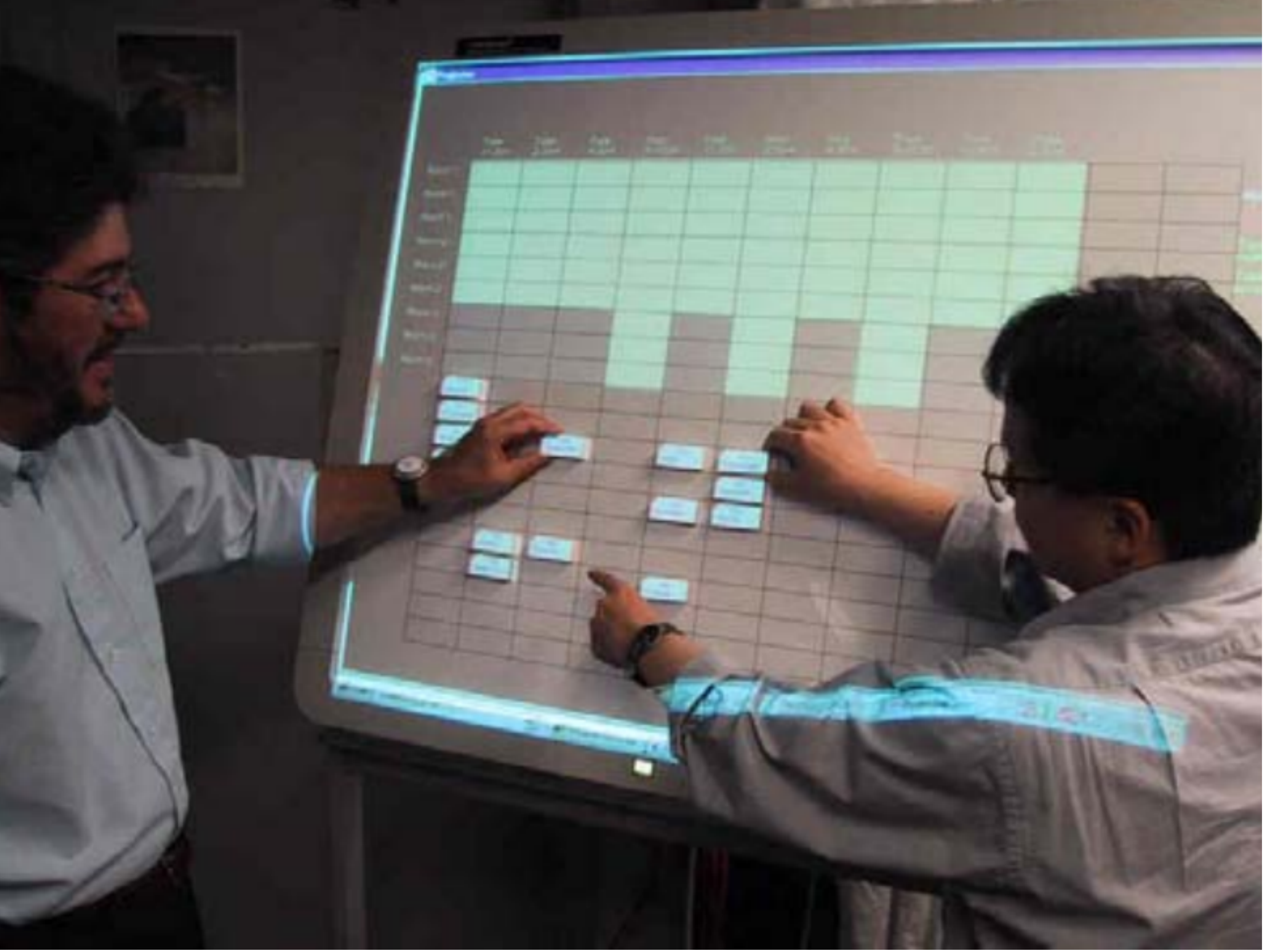
Figure 1: A flexible "artist's curve" constraining the motion of a cellphone tower in the Pico system.

ical process. The user can leverage his or her mechanical intuition about the way physical objects respond to forces and interact with each other to understand how common objects, such as a rubber band or coffee cup, might be used to constrain the underlying software process.

Objects on the Pico table are moved not only under software control using electromagnets but also by users standing around the table. The combination of these interactions, all governed by the friction and mass of the objects themselves directly affects the result of the task being performed. Additional information is graphically projected onto the table from above. In this paper we will show how this technique

location, neighborhood, and state::

tangibles become more meaningful,
the more information they encode in a mapping-free way



2002: Jacob: Sensetable: location meaningful

A Tangible Interface for Organizing Information Using a Grid

Robert J.K. Jacob*, Hiroshi Ishii, Gian Pangaro, and James Patten
Tangible Media Group, MIT Media Laboratory , Cambridge, Mass. USA
{rjacob, ishii, pangaro, jpatten}@media.mit.edu

ABSTRACT
The task of organizing information is typically performed either by physically manipulating note cards or sticky notes or by arranging icons on a computer with a graphical user interface. We present a new tangible interface platform for manipulating discrete pieces of abstract information, which attempts to combine the benefits of each of these two alternatives into a single system. We developed interaction techniques and an example application for organizing conference papers. We assessed the effectiveness of our system by experimentally comparing it to both graphical and paper interfaces. The results suggest that our tangible interface can provide a more effective means of organizing, grouping, and manipulating data than either physical operations or graphical computer interaction alone.

Keywords
Tangible user interfaces, physical interaction, computer-supported cooperative work, sensing board, conference planning, scheduling, direct manipulation, experiment.

INTRODUCTION
Tangible user interfaces (TUI) have been most compelling in spatial or geometric application domains such as urban planning[15], where the physical arrangement of the objects to be manipulated has an obvious, inherent meaning in the application. We want to explore the use of tangible user interfaces in a wider range of more abstract information tasks, where they have been less fully notecards on a desk or, by collaboratively arranging sticky notes on a board. Such arrangement often begins in a free-form way, by accreting small groups of related items, and, later, develops into a larger structure or framework. Tasks like this have thus far been surprisingly resistant to computer support, perhaps because notecards or sticky notes allow manipulation that is more natural and fluid and particularly, free form without a predefined framework. Even when the information to be organized already exists in electronic form and the final output must be produced in digital form, many people find it advantageous to copy the information onto pieces of paper, manipulate them manually, and then re-enter the resulting organization into the computer.

1995: Suzuki: AlgoBlocks, neighborhood of blocks meaningful

Interaction-Level Support for Collaborative Learning: *AlgoBlock* — An Open Programming Language

Hideyuki Suzuki and Hiroshi Kato

Information Technology Research Laboratories
NEC Corporation

Abstract

In this paper, the role of computer-based educational tools is discussed from the standpoint of situated learning theory (e.g., Brown et al. 1988, Lave et al. 1991), which considers learning to be a process of enculturation in a community of practice (Lave et al. 1991). The authors propose, as one possibility, the role of computer-based educational tools as supporters of a "community of learners". "Community of learners" is a community maintained by "learners" who are trying to establish their identities in a certain community of practice. It works as an interface to full participation in the community of practice. Both facilitating interactions among learners and making links between activities within the community of learners and practices in the real world are crucial for supporting the community of learners. As the first step to this goal, the authors focus on interaction-level support of the community of learners, and mention AlgoBlock, a tangible programming language developed by the authors, as an example of computer-based educational tools for facilitating interactions among learners.

Keywords — Community of learners, Software Edu-

one's action is achieved as a result of interaction with the external world by utilizing some kinds of artifacts as a medium (Cole et al. 1980). It is important that the artifacts carry a history of some culture of practice, and they can be understood only when observed through that culture of practice which is creating and maintaining them. The artifacts are continuously reproduced in activities of the communities through works, and one consequently can "acknowledge" the meaning of artifacts through participation in the activities.

Given that one's action is considered to be achieved through utilizing artifacts as media, learning cannot be separable from artifacts. Furthermore, if artifacts cannot be dissociated from the practice of a community, learning should be considered to be a process of participating in a culture of practice (Brown et al. 1988). Thus learning is considered to be a process of enculturation. Based upon this idea, Lave et al. (1991) proposed a concept of legitimate peripheral participation, i.e., LPP. LPP is a learning principle in which one's learning is described as process of development of participation in a community that proceed gradually from peripheral to full.

2007: Merrill: Siftables: neighborhood of blocks meaningful

2007: Merrill: Siftables: neighborhood of blocks meaningful

Siftables: Towards Sensor Network User Interfaces

David Merrill
MIT Media Laboratory
20 Ames St., E15-320B.
Cambridge, MA 02139, USA
dmerrill@media.mit.edu

Jeevan Kalanithi
MIT Media Laboratory
20 Ames St., E15-357.
Cambridge, MA 02139, USA
jeevan@media.mit.edu

Pattie Maes
MIT Media Laboratory
20 Ames St., E15-315.
Cambridge, MA 02139, USA
pattie@media.mit.edu

ABSTRACT
This paper outlines Siftables, a novel platform that applies technology and methodology from wireless sensor networks to tangible user interfaces in order to yield new possibilities for human-computer interaction. Siftables are compact devices with sensing, graphical display, and wireless communication. They can be physically manipulated as a group to interact with digital information and media. We discuss the unique affordances that a sensor network user interface (SNUI) such as Siftables provides, as well as the resulting directness between the physical interface and the data being manipulated. We conclude with a description of some gestural language primitives that we are currently prototyping with Siftables.

Author Keywords
Sensor Network User Interface (SNUI), Tangible User Interface (TUI), Sensor Network, Siftable Computing Interface

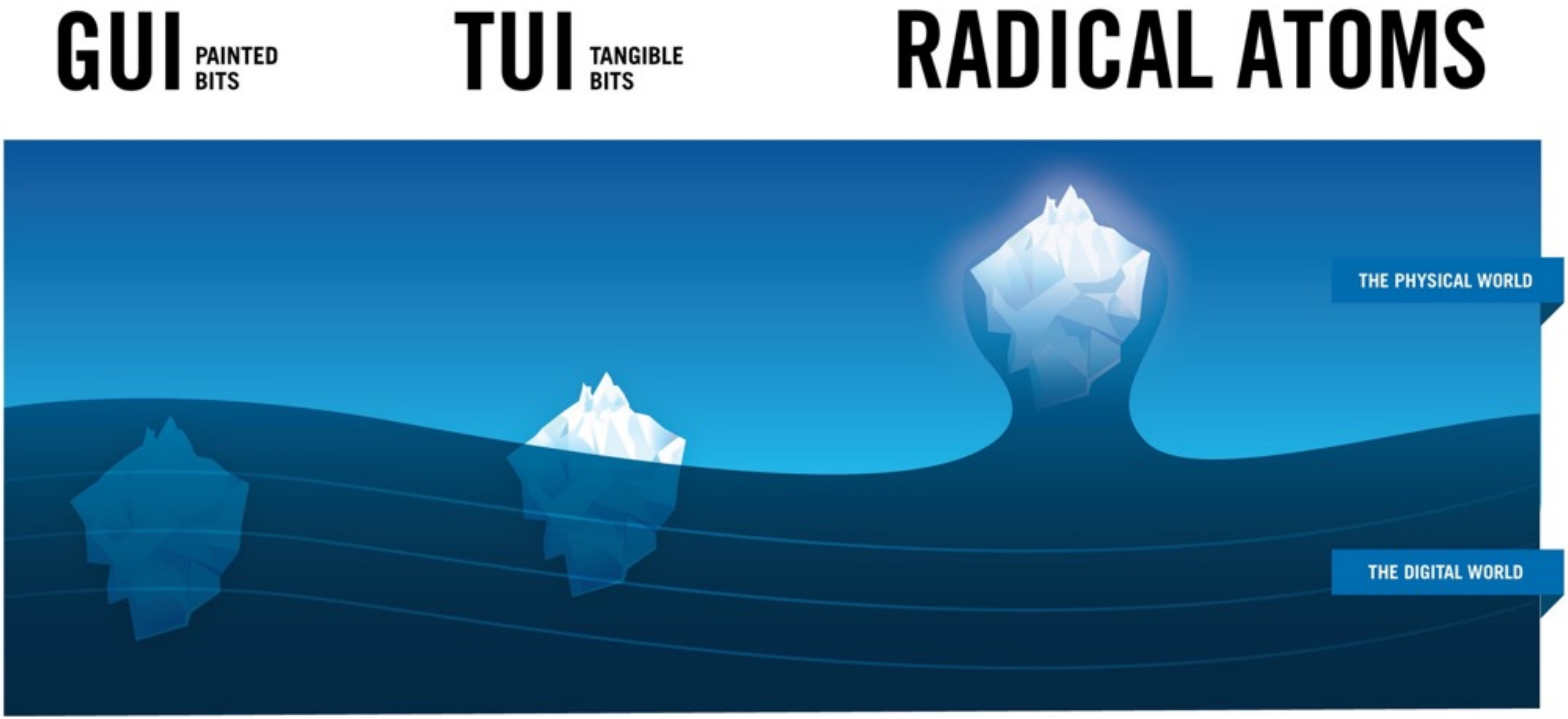
ACM Classification Keywords
H.1.2: Models and Principles: User/Machine Systems. H.5.2: Information Interfaces and Presentation: User Interfaces. K.8.0: Personal Computing: General. J.7: Computer Applications: Computers in Other Systems.

INTRODUCTION
The development of new technologies often spurs new ideas we propose applying principles from sensor network technologies to TUI research in order to open up new interaction possibilities. We call this class of distributed TUIs Sensor Network User Interfaces (SNUIs)[2].

We first compare some existing HCI paradigms to the possibilities afforded by a distributed tangible user interface (dTUI). We then discuss Siftables, an example of the dTUI. Next we sketch out some elements of an interaction language for Siftables. We conclude with challenges and future work in this area.

BACKGROUND AND MOTIVATION
The design of Siftables was inspired by observing the skill that humans have at sifting, sorting, and otherwise manipulating large numbers of small physical objects. When we overturn a container of nuts and bolts and sift through the resulting pile to find one of a particular size, or spread photographs out on a tabletop and sort them into piles, we use all of our fingers and both hands actively and efficiently. However, when we sort digital information or media such as digital photographs or emails, the experience typically does not leverage our physical manipulation skills. One typical user interaction with a modern graphical user interface (GUI) is to click on an icon with the mouse, drag it to another location on the screen, and drop it to reposition it or to assign the data it represents to a folder. This so-called 'direct manipulation'

where will it lead…



2012: Hiroshi Ishii’s vision: Radical Atoms

merges with Ivan Sutherland's vision of 'The Ultimate Display'

"The ultimate display would, of course, be a room within which the **computer can control the existence of matter.**

— I. Sutherland, The Ultimate Display, *Proc. IFIP 65*, 506–508, 1965

2004: Claytronics vision (not implemented)

Claytronics: An Instance of Programmable Matter

Seth Copen Goldstein and Todd Mowry
{seth,tcm}@cs.cmu.edu
Carnegie Mellon University

Programmable matter refers to a technology that will allow one to control and manipulate three-dimensional physical artifacts (similar to how we already control and manipulate two-dimensional images with computer graphics). In other words, programmable matter will allow us to take a (big) step beyond virtual reality, to *synthetic reality*, an environment in which all the objects in a user's environment (including the ones inserted by the computer) are *physically* realized. Note that the idea is not to transport objects nor is it to recreate an objects chemical composition, but rather to create a physical artifact that will mimic the shape, movement, visual appearance, sound, and tactile qualities of the original object.

The enabling hardware technology behind synthetic reality is Claytronics, a form of programmable matter that can organize itself into the shape of an object and render its outer surface to match the visual appearance of that object. Claytronics is made up of individual components, called *catoms*—for Claytronic atoms—that can move in three dimensions (in relation to other catoms), adhere to other catoms to maintain a 3D shape, and compute state information (with possible assistance from other catoms in the ensemble). In our preliminary designs, each catom is a self-contained unit with a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms.

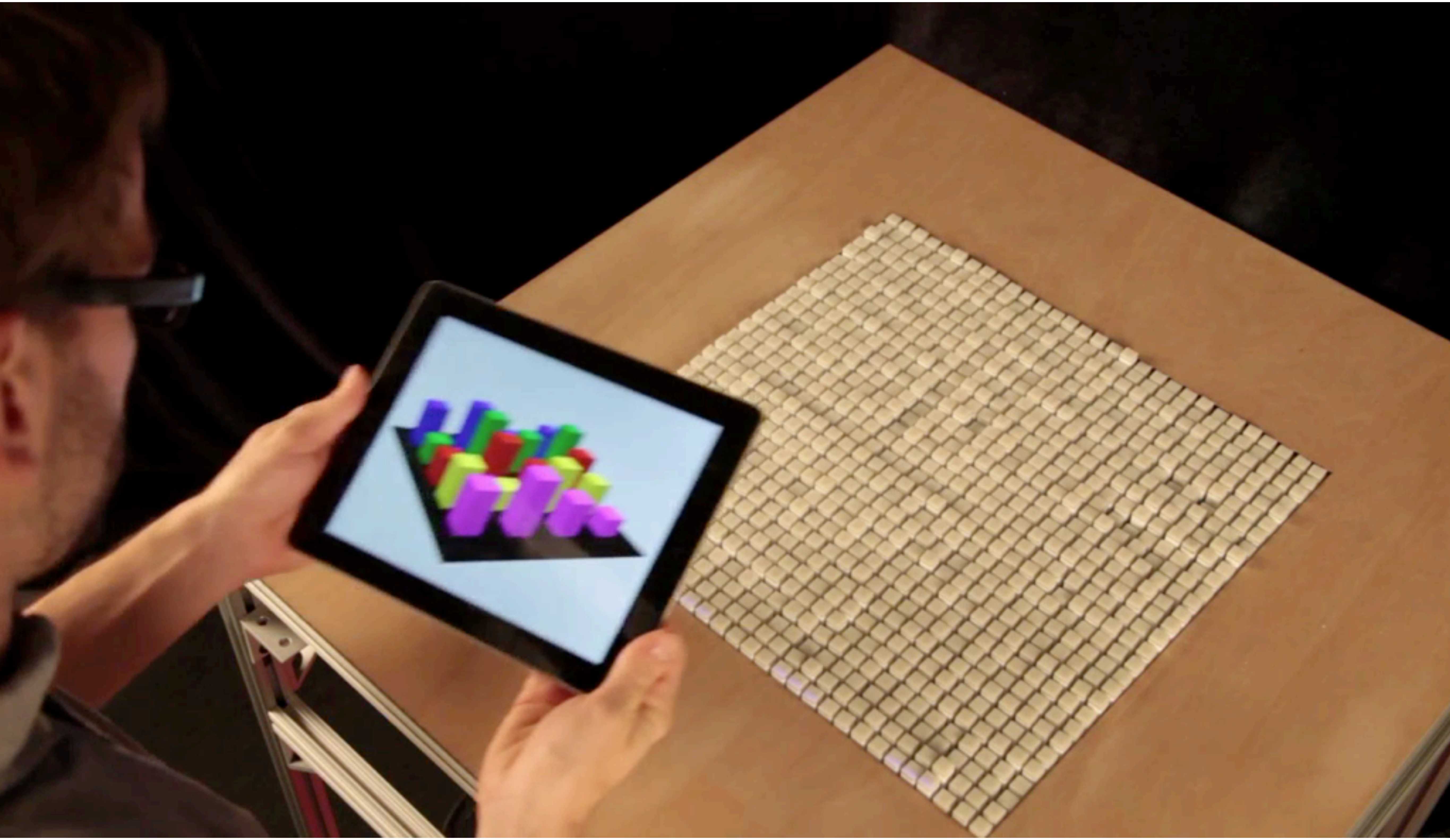
Creating a physical replica of an arbitrary moving 3D object that can be updated in real time involves many challenges. The research involved in addressing these scientific challenges is likely to have broad impact beyond synthetic reality. Particularly relevant to the ASPLOS com-

(mimicking a human form) would then be specified abstractly, perhaps as a series of "snapshots" or as a collection of virtual deforming "forces", and then broadcast to the catoms. Compilation of the specification would then provide each catom with a local plan for achieving the desired global shape. At this point, the catoms would start to move around each other using forces generated on-board, either magnetically or electrostatically, and adhere to each other using, for example, a nanofiber-adhesive mechanism [4]. Finally, the catoms on the surface would display an image; rendering the color and texture characteristics of the source object. If the source object begins to move, a concise description of the movements would be broadcast allowing the catoms to update their positions by moving around each other. The end result is that the system appears to be a single coordinated system.

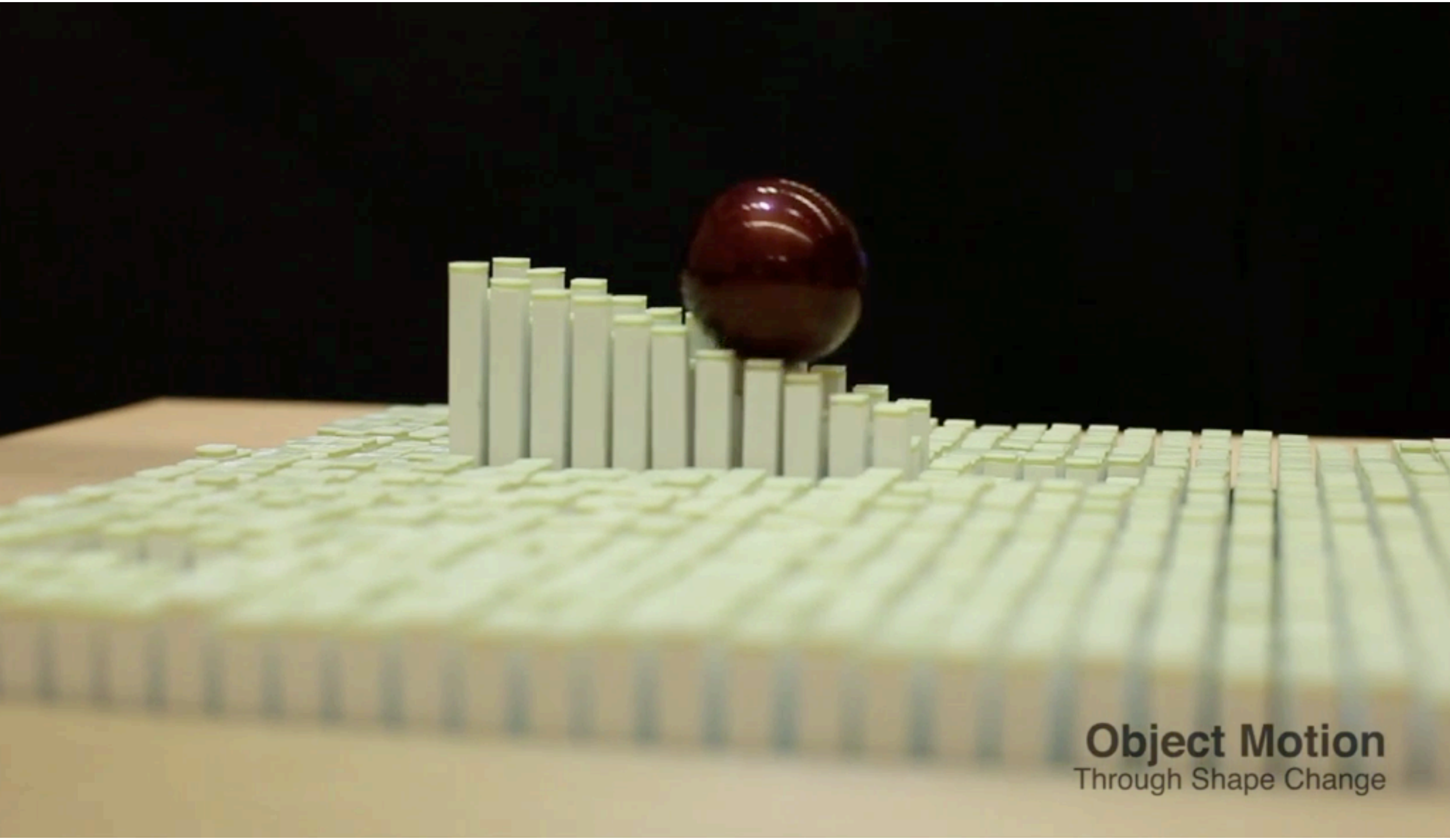
One key motivation for our work is that technology has reached a point where we can realistically build a programmable matter system which is guided by design principles which will allow it to ultimately scale to millions of sub-millimeter catoms. In fact, we expect our prototype for 2D Claytronics to be operational before ASPLOS'04.

Our goal is that the system be usable now and scalable for the future. Thus, the guiding design principle, behind both the hardware and the software, is scalability. Hardware mechanisms need to scale towards micron-sized catoms and million-catom ensembles. For example, the catom hardware minimizes static power consumption (e.g., no static power is used for adhesion) and avoids moving parts (e.g., the locomotion mechanism currently uses magnetic forces). Software mechanisms need to be scale invariant. For example, our localization and orientation algorithms are completely distributed, parallel, and, are indifferent to catom size.

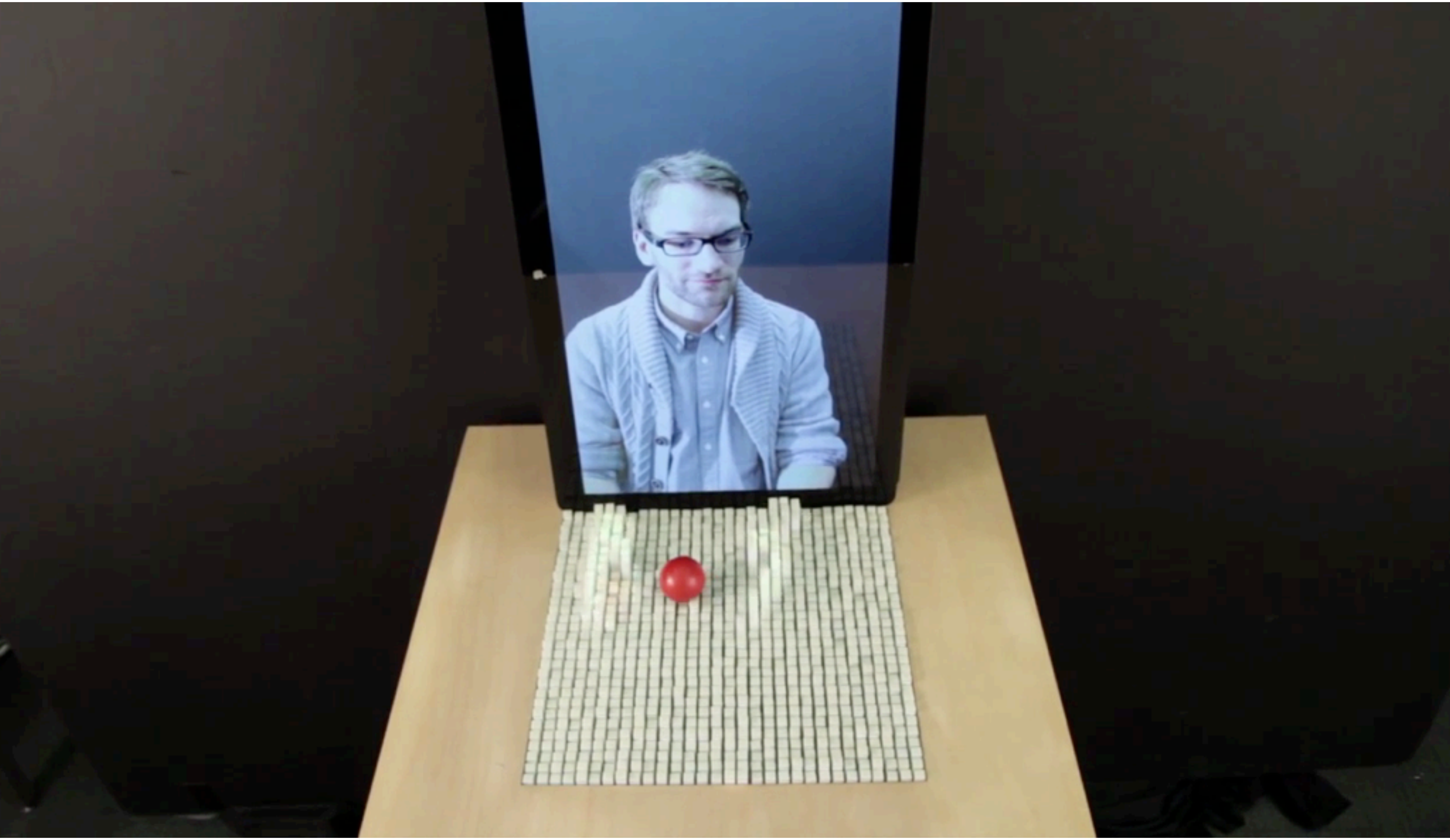
Claytronics will be a test-bed for solving some of the most challenging problems we face today: how to build complex, massively distributed dynamic systems. It is also a step towards truly integrating computers into our lives—by having them integrated into the very artifacts



2013: Leithinger, Ishii: inForm shape display



2013: Leithinger, Ishii: inForm shape display



2013: Leithinger, Ishii: inForm shape display

inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation

Sean Follmer* **Daniel Leithinger*** **Alex Olwal** **Akimitsu Hogge** **Hiroshi Ishii**
MIT Media Lab
75 Amherst Street, Cambridge, MA 02139, USA
{sean, daniell, olwal, ishii}@media.mit.edu

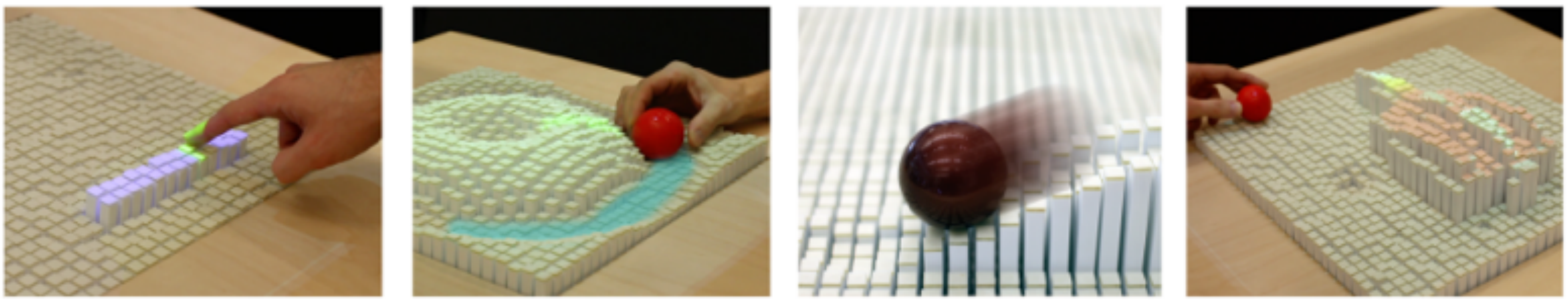


Figure 1: inFORM enables new interaction techniques for shape-changing UIs. *Left to right:* On-demand UI elements through *Dynamic Affordances*; Guiding interaction with *Dynamic Constraints*; Object actuation; Physical rendering of content and UI.

ABSTRACT

Past research on shape displays has primarily focused on rendering content and user interface elements through shape output, with less emphasis on dynamically changing UIs. We propose utilizing shape displays in three different ways to mediate interaction: to *facilitate* by providing dynamic physical affordances through shape change, to *restrict* by guiding users with dynamic physical constraints, and to *manipulate* by actuating physical objects. We outline potential interaction techniques and introduce *Dynamic Physical Affordances and Constraints* with our inFORM system, built on top of a state-of-the-art shape display, which provides for variable stiffness rendering and real-time user input through direct touch and tangible interaction. A set of motivating examples demonstrates how dynamic affordances, constraints and object actuation can create novel interaction possibilities.

Author Keywords

INTRODUCTION

The rich variety of physical forms found in everyday life often serve both functional and aesthetic roles. These physical objects have features that not only provide functionality, but also suggest possible uses, or confine the ways we may interact with them; Norman labels these as perceived affordances [30]. This notion of perceived affordances has been long appropriated by the HCI field, particularly in the context of Graphical User Interfaces (GUI) and Tangible User Interfaces (TUI) [17]. While GUIs have the ability to change perceived affordances rapidly to adapt them to different content and context, TUIs primarily exploit the affordances inherent in physical form, as well as their physiological and cognitive advantages [21]. For example, the Token and Constraint framework introduced by Ullmer uses mechanical constraints to provide physical affordances for interacting with tangible controllers, such as tokens [38]. However, TUIs, such as those outlined by Ullmer, are often limited by the end.