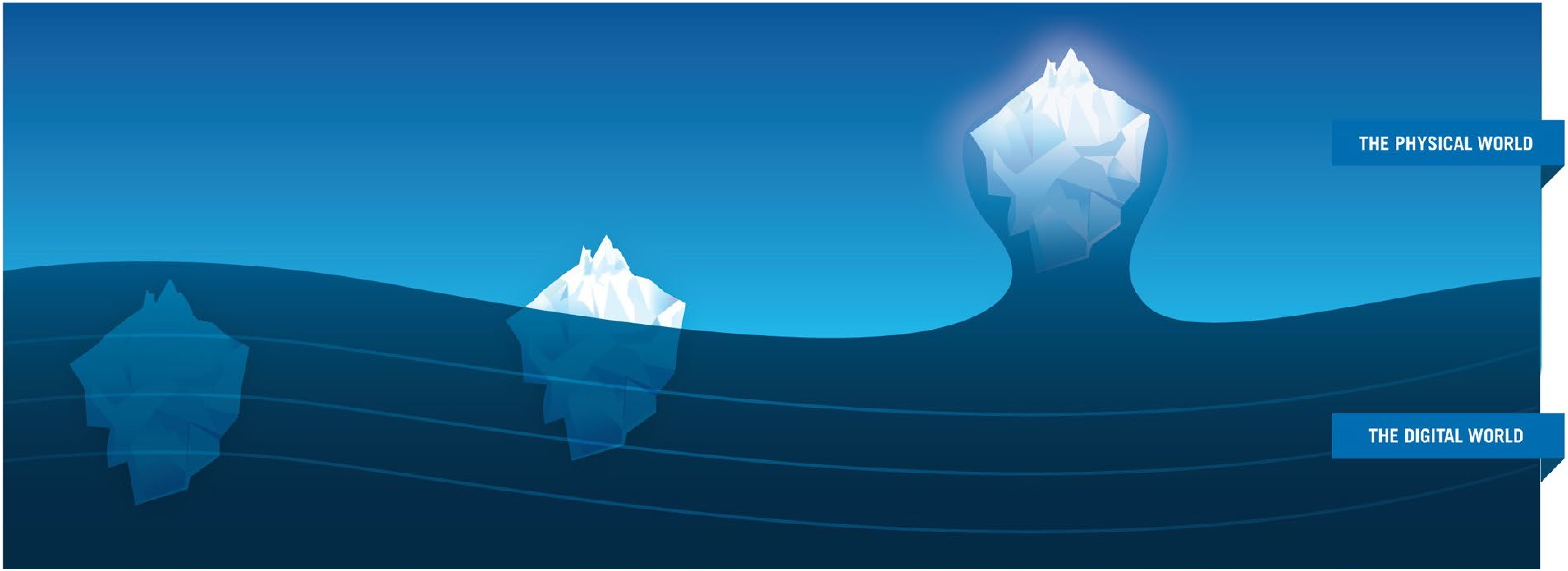
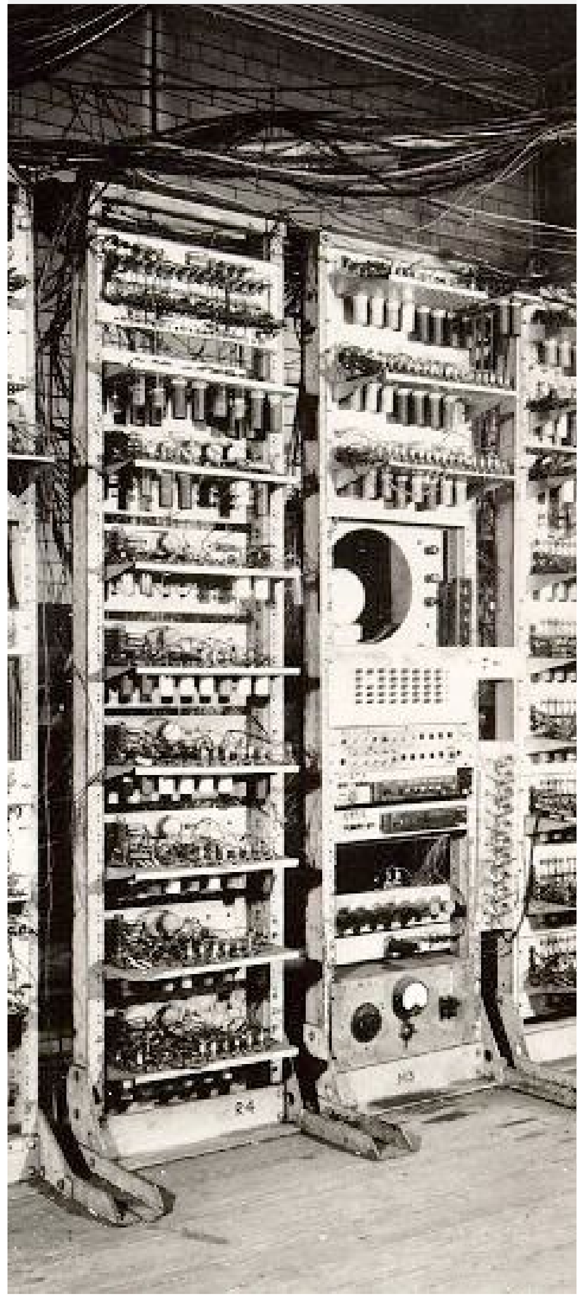


Tangible User Interface

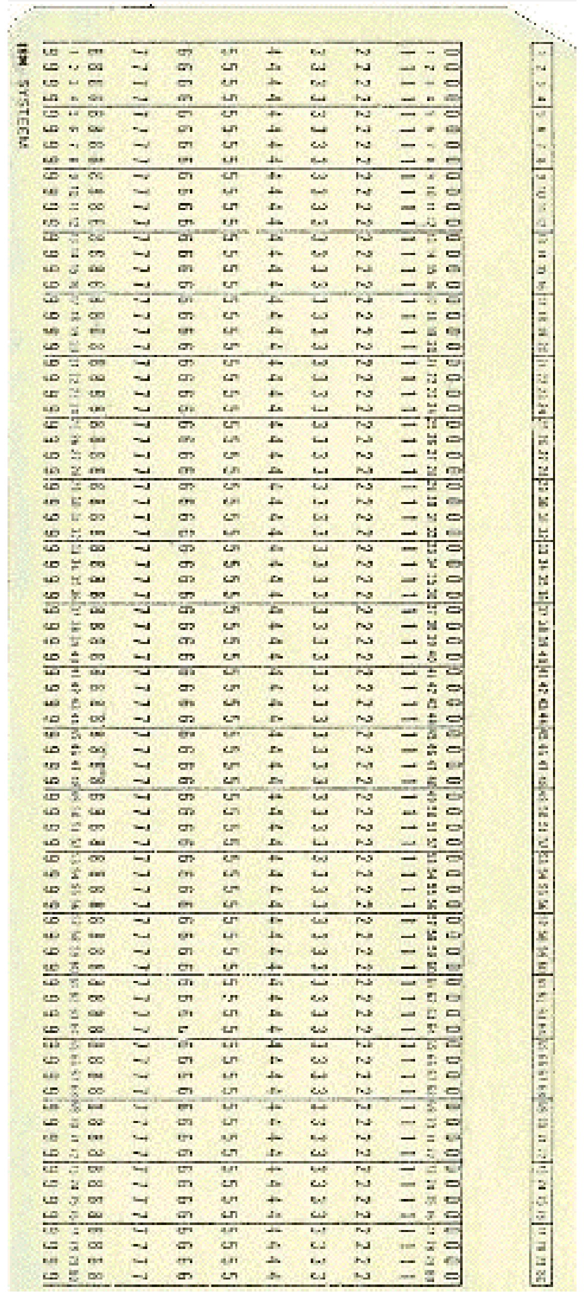
Huaishu Peng | UMD CS | Fall 2022

Historical Development of UI

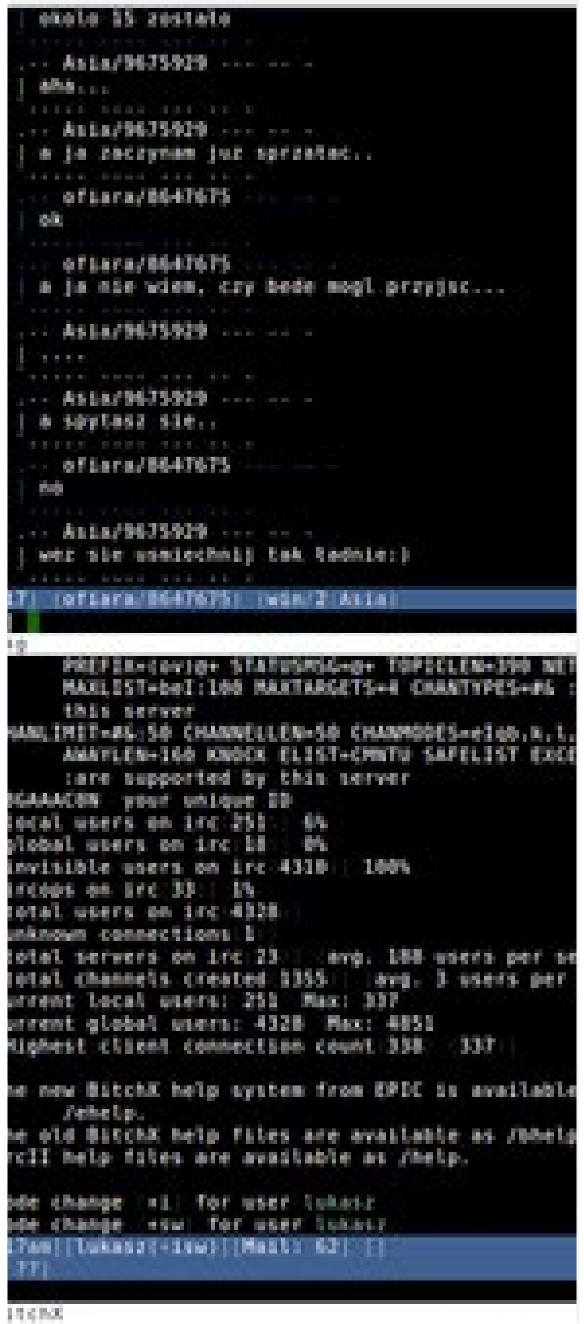
Electrical



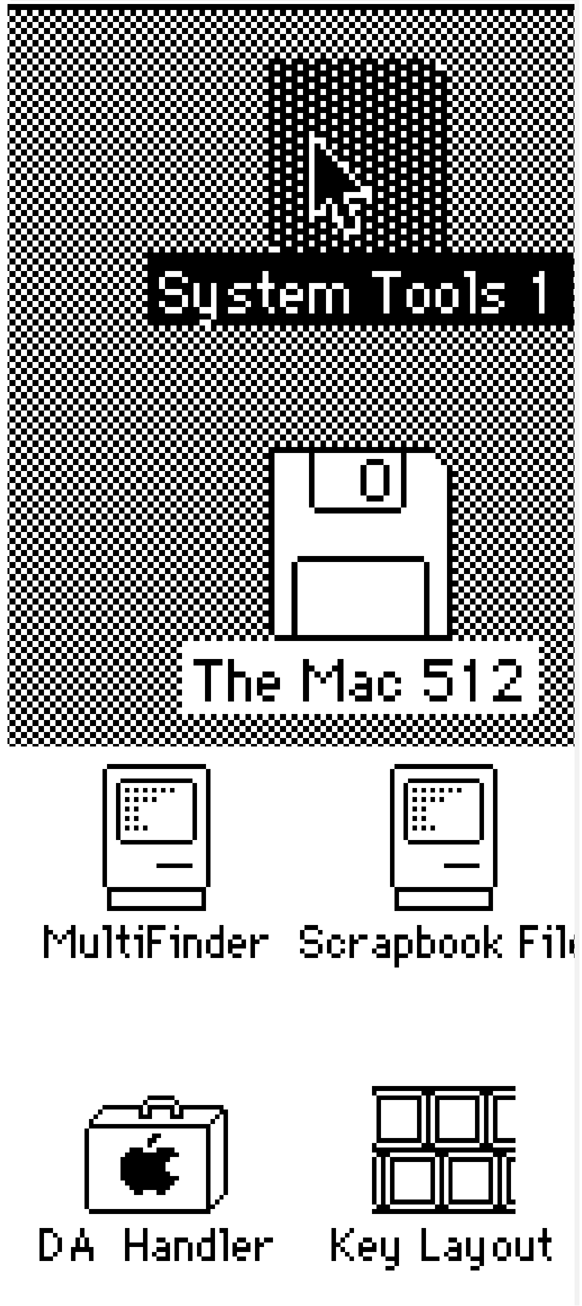
Symbolic



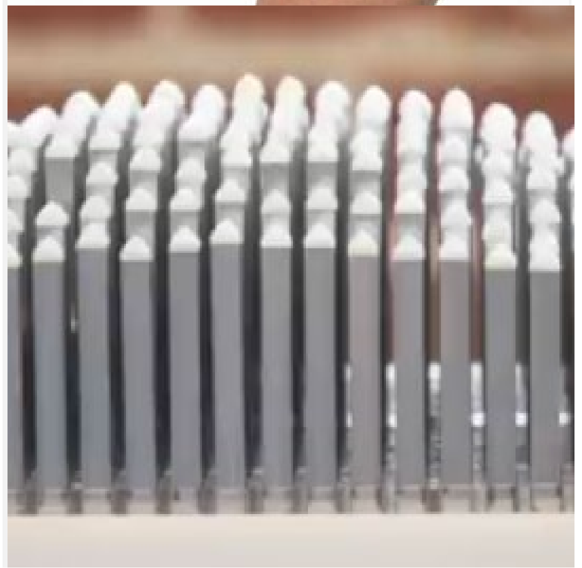
Textual



Graphical

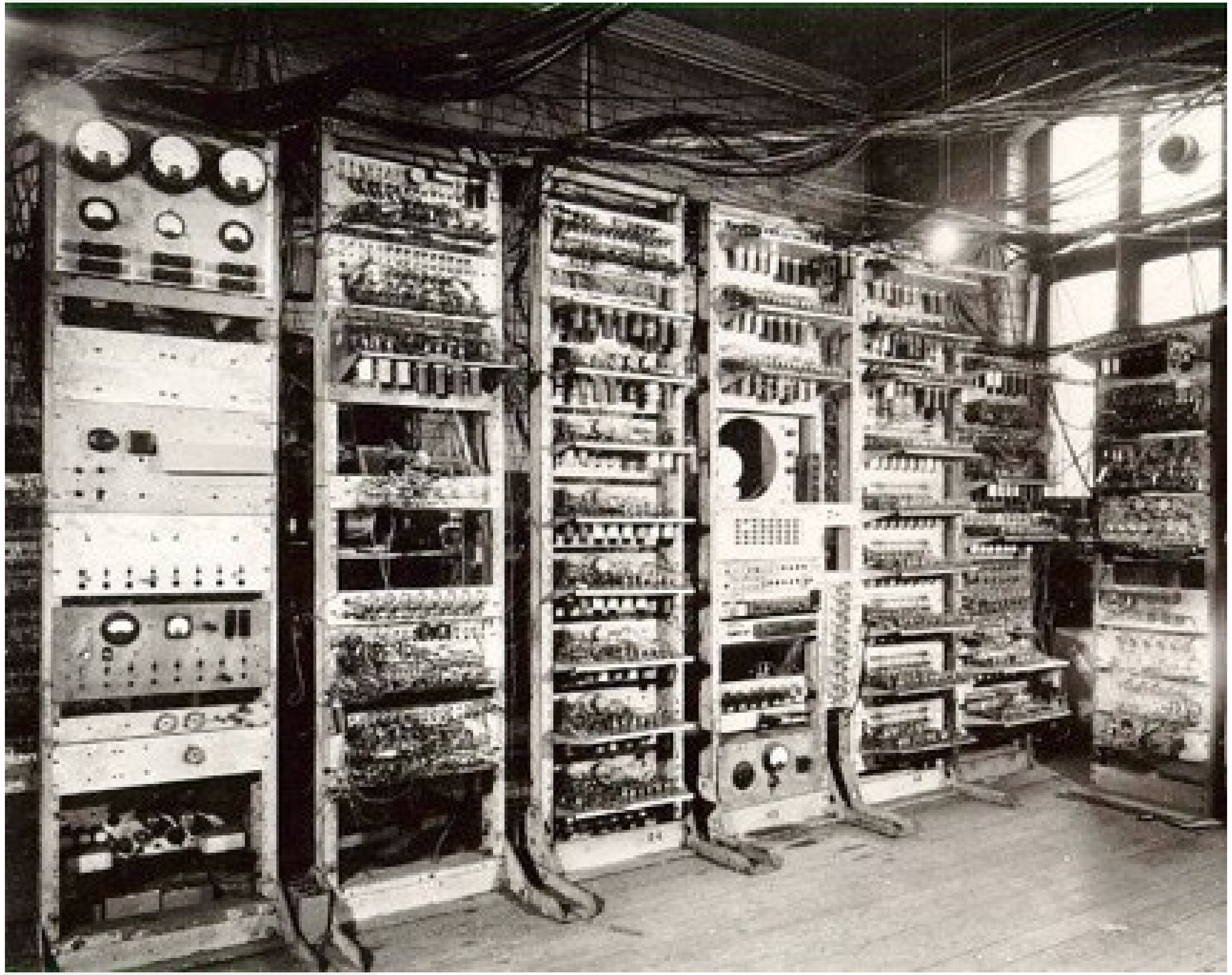


Embodied



From Where the Action Is (Dourish, 2001)

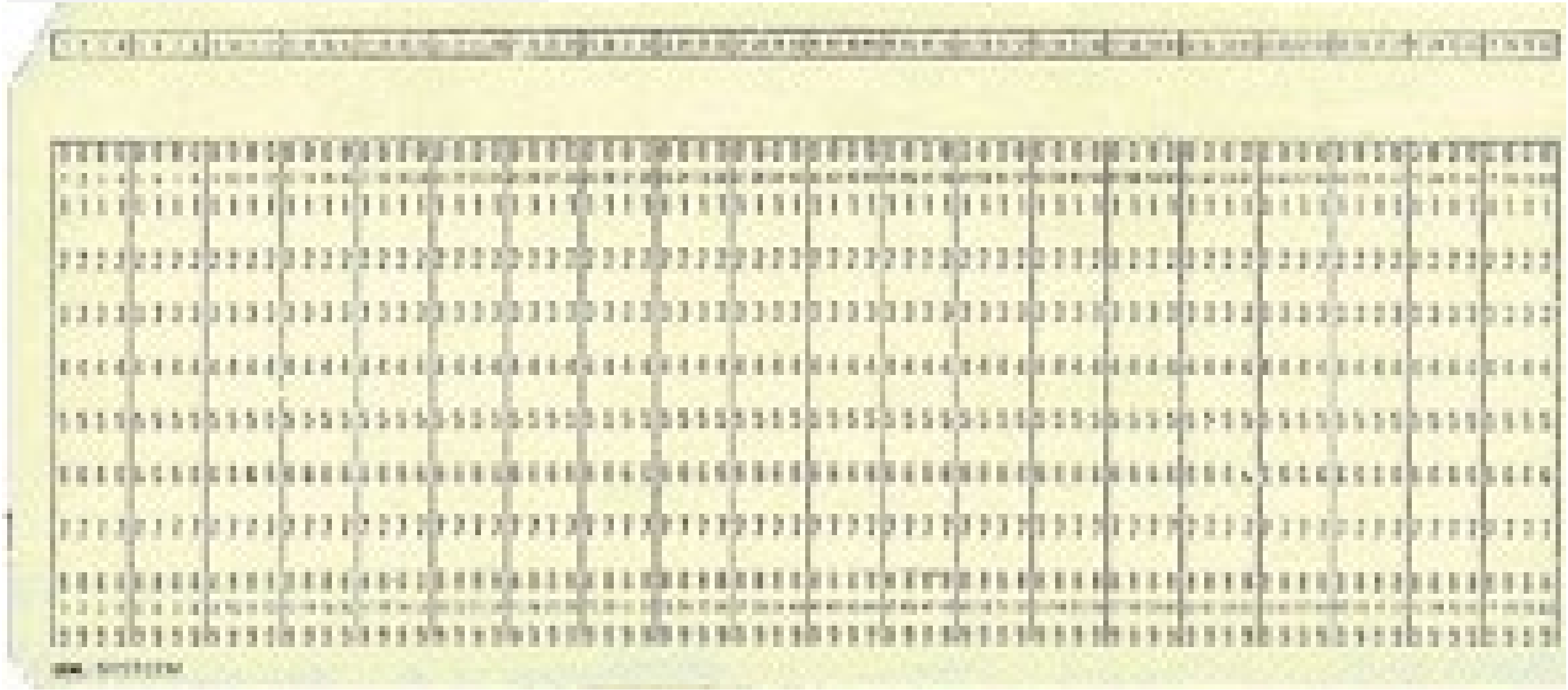
Electrical



The Small Scale Experimental Machine, AKA “Baby” built at Manchester University in 1948.

- Special purpose devices (e.g., automatic calculation of missile trajectories, patterns in coded messages)
- Held a sequence of instructions in its memory.
- To program the machine for different tasks, electrical circuits need to be changed
- Interacting with the system required a thorough understanding of the electronic design

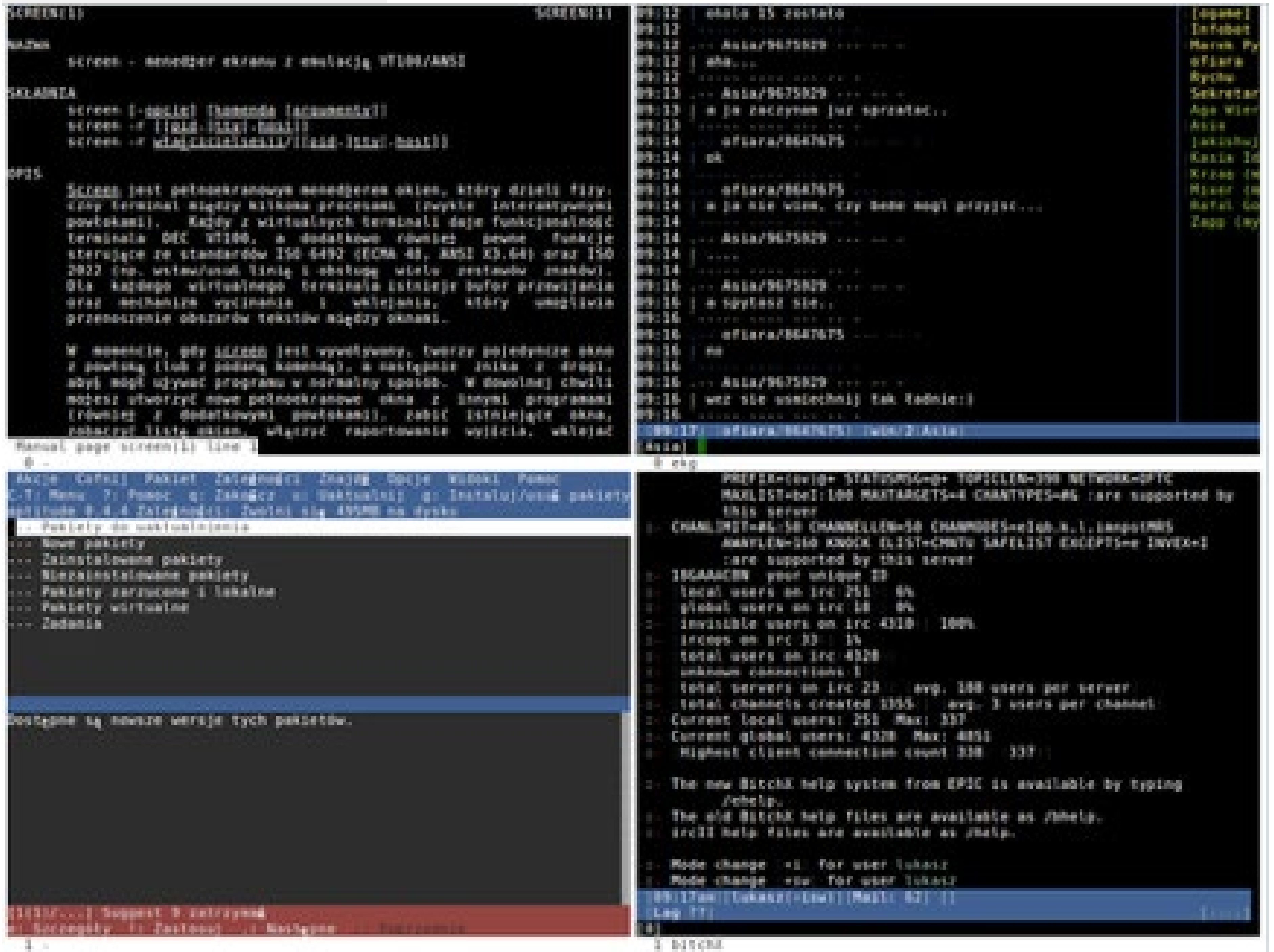
Symbolic



IBM 29 card punch (circa 1950's)

- Introduction of programming systems (e.g.,assemblers)
- Symbolic forms of interaction is not textual (e.g., punched cards)
- More regularized instructions available across a wider range of machines

Textual

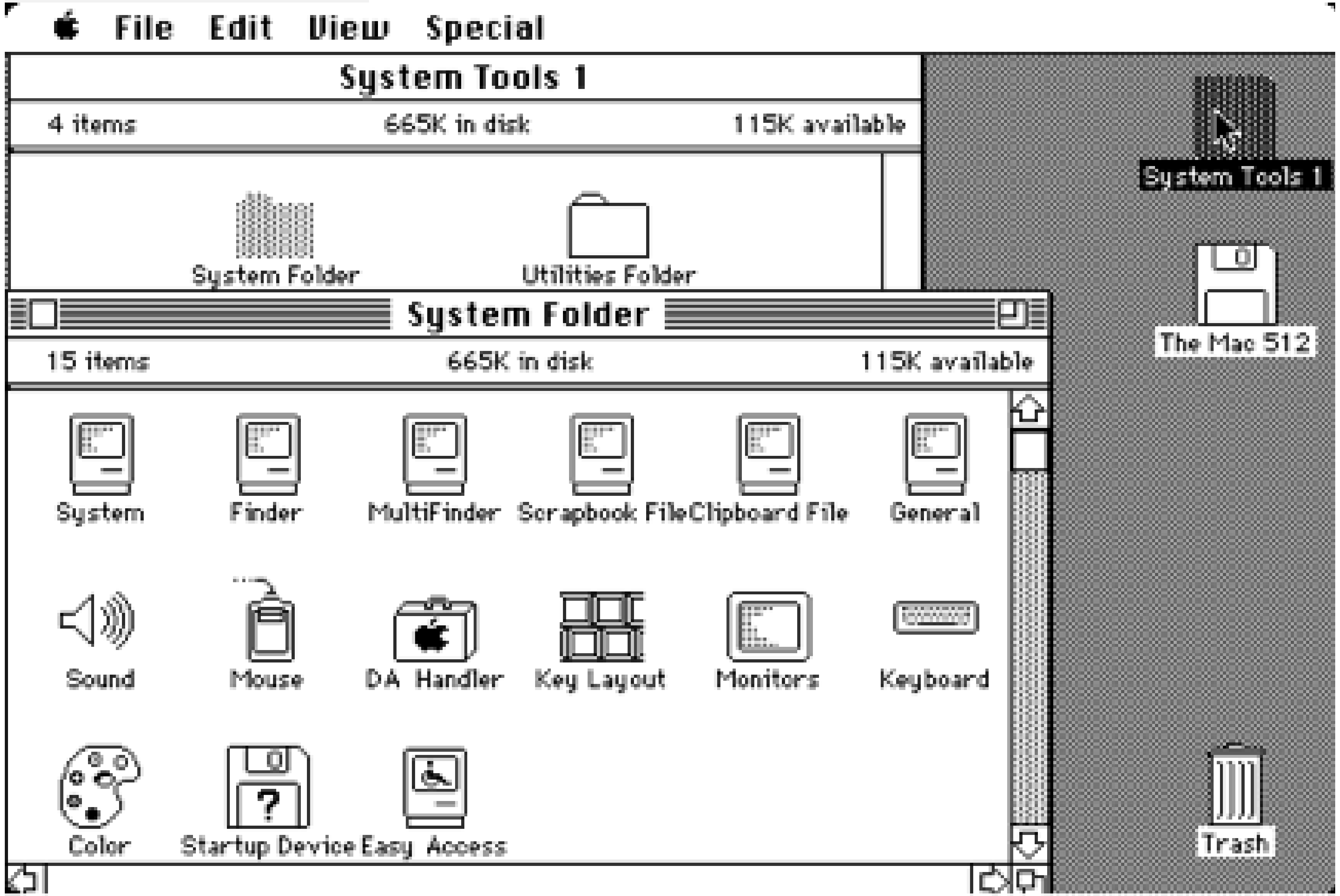


E.g., early UNIX, DOS

- Takes advantage of the best-developed form of symbolic interaction: written language

- More like a “dialog”

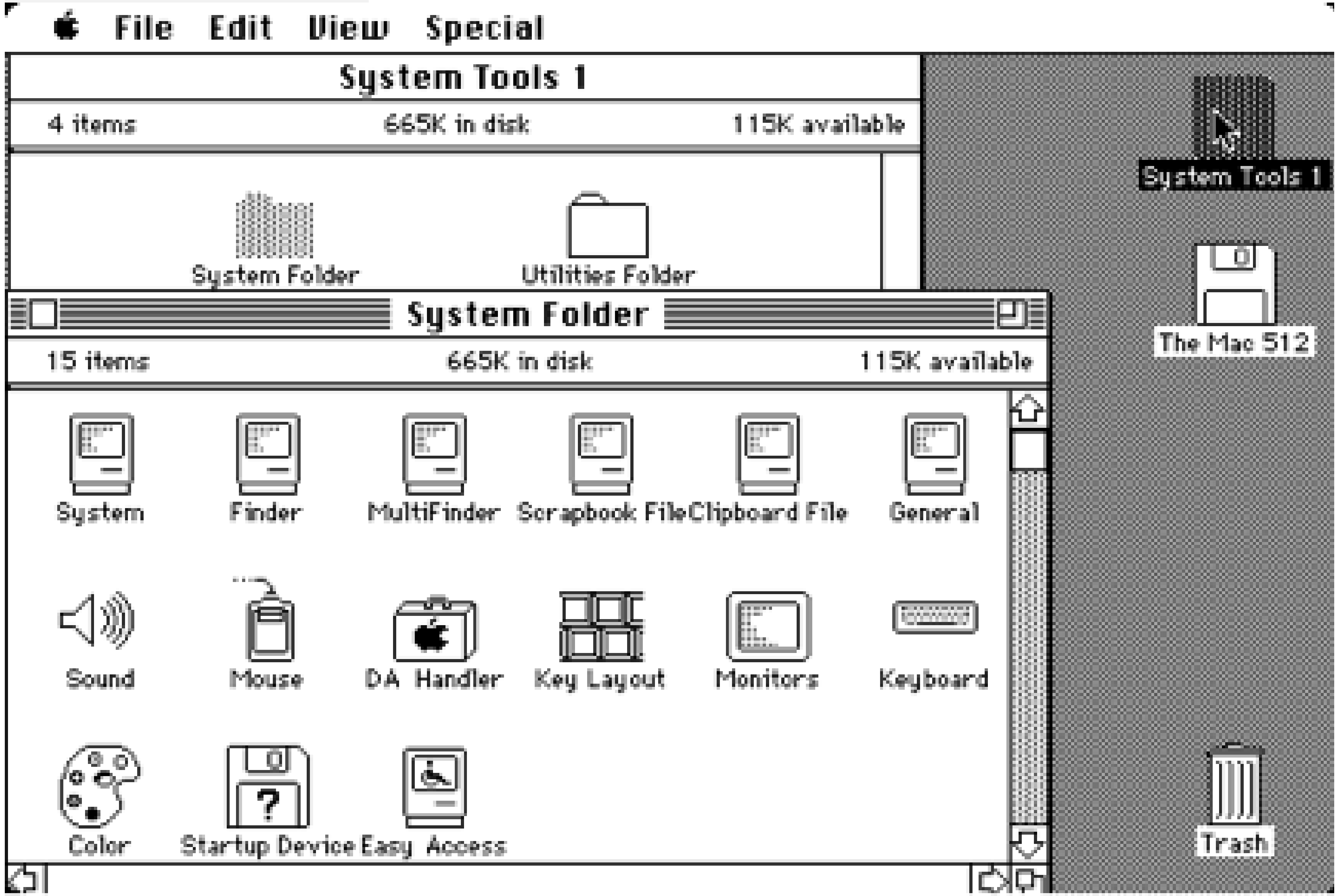
Graphical



Macintosh System 4.2, 1987

Turning interaction into two-dimensional space rather than a one-dimensional stream of characters

Graphical



Macintosh System 4.2, 1987

Exploit more sets of human skills:

- Peripheral Attention

Primary space, secondary space (e.g., windows and dashboards)

- Pattern recognition and spatial reasoning

Opportunities to arrange data spatially

- Information density

A picture really can be worth a thousand words (e.g., diagrams)

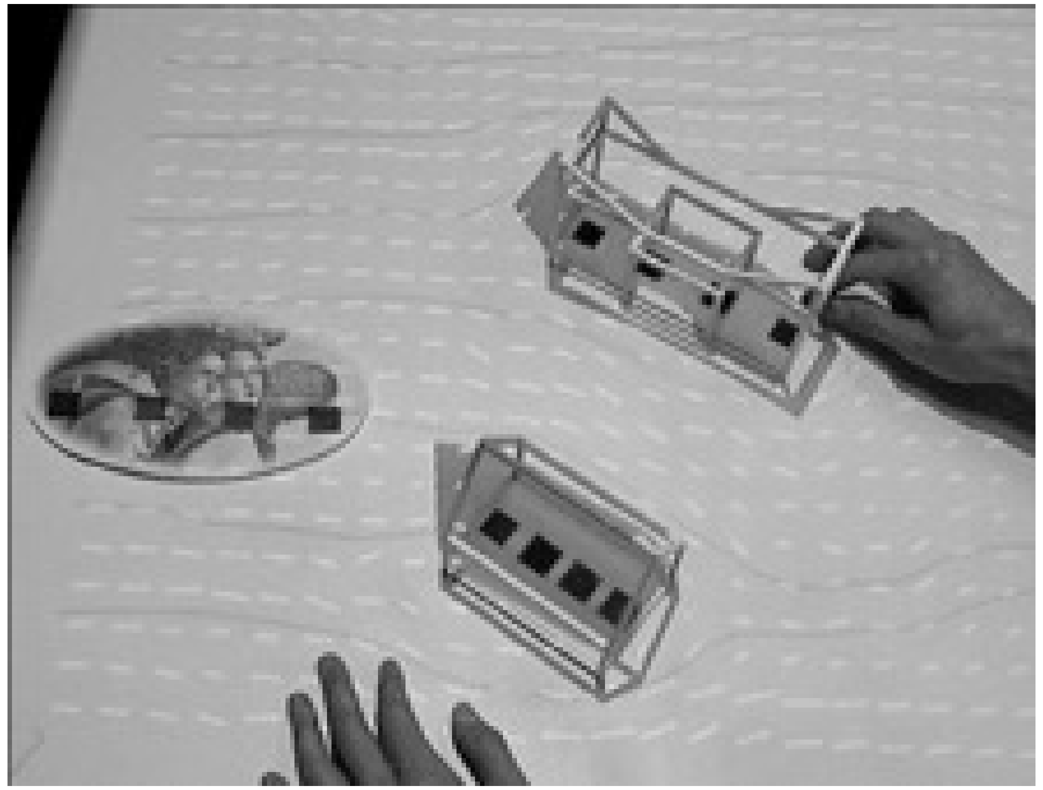
- Visual metaphors

File cabinets, trash cans, desktop tools

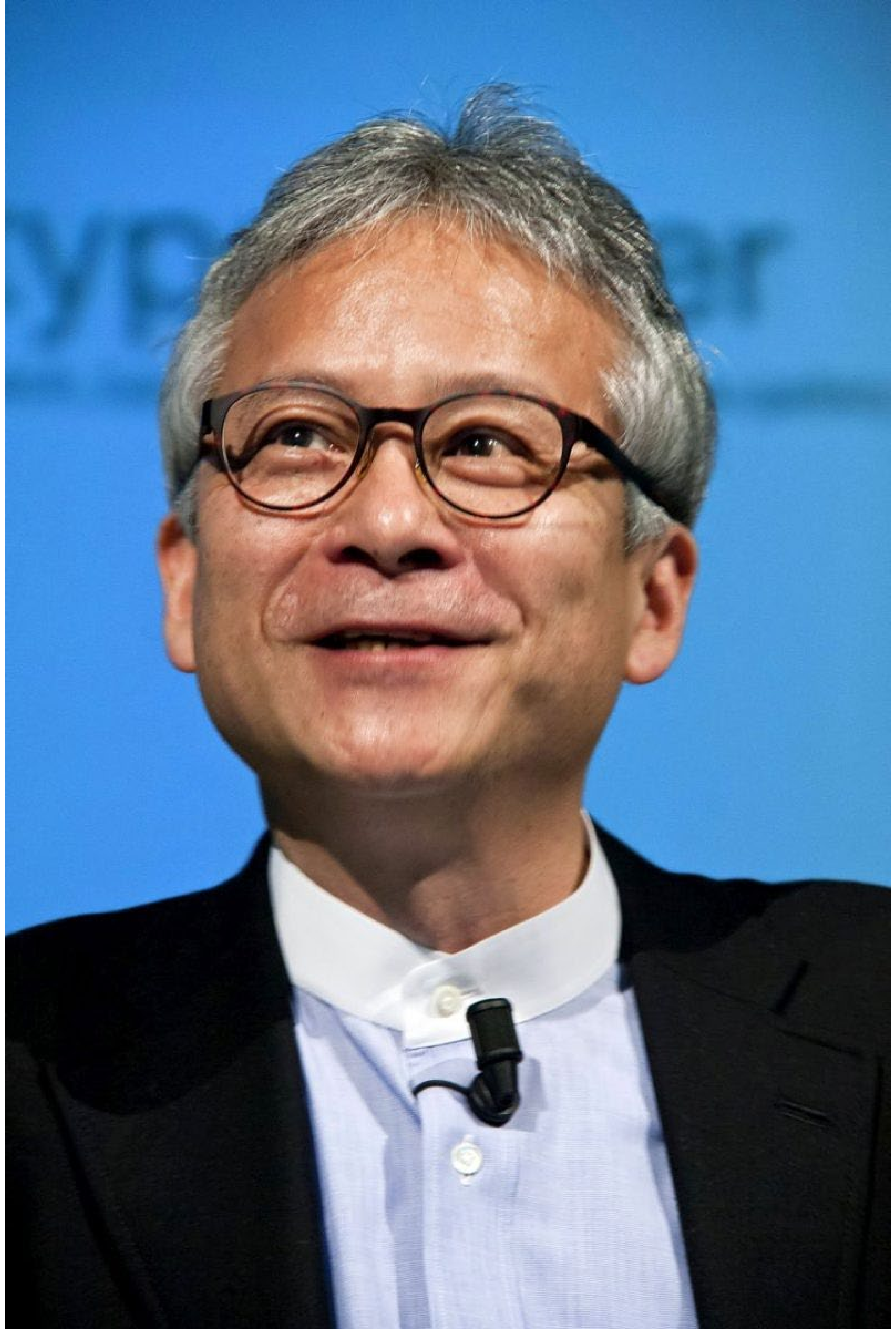
Tangible

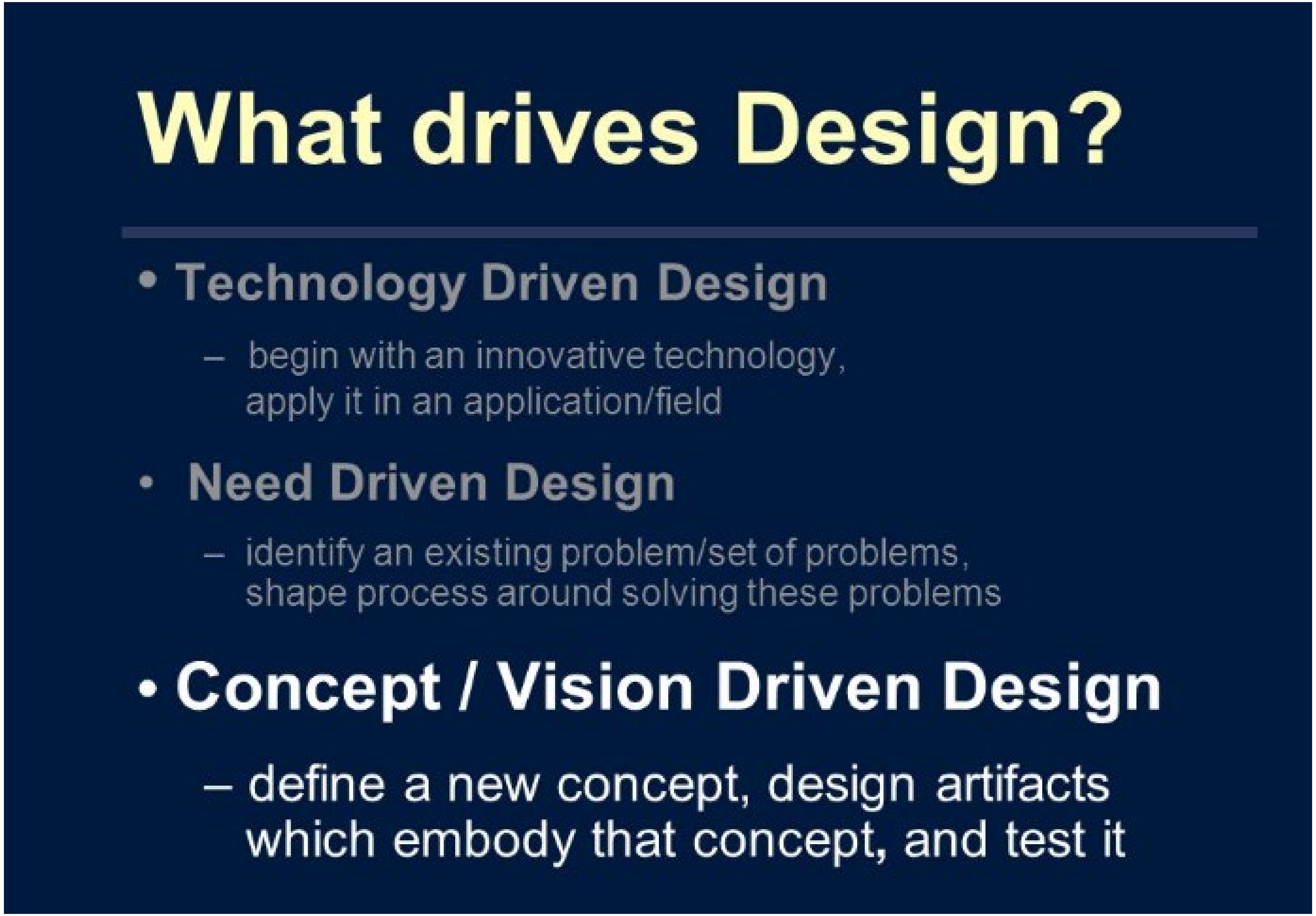

Computation that moves beyond desktop

• Interaction is incorporated more richly in our daily experience of the physical world

Hiroshi Ishii
MIT Media Lab
Tangible Media Group





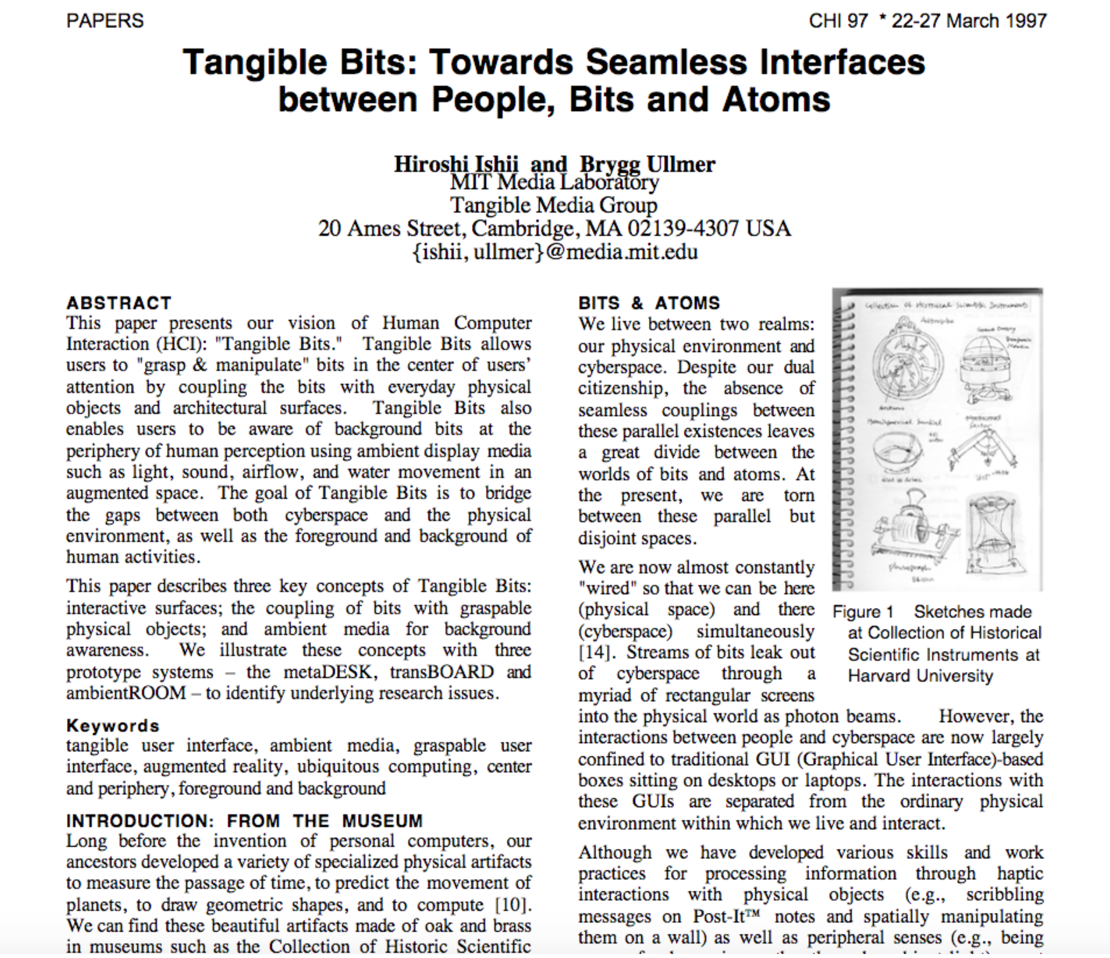
Vision driven research

Typical HCI

GUI of desktop PC

Tangibl

World wil



PAPERS CHI 97 * 22-27 March 1997

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 in museums such as the Collection of Historic Scientific

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.

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

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

UIST 1997
Ishii and Ullmer

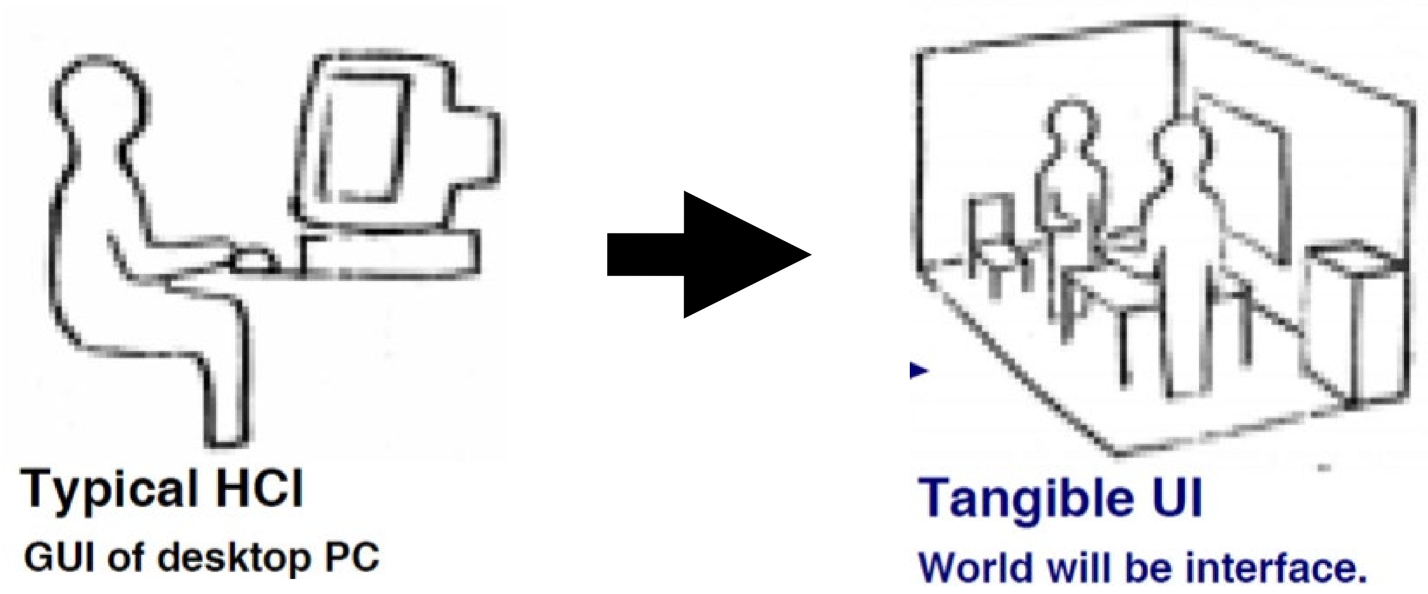
1997: Ishii: long term vision for Tangible User Interfaces

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.

One example

UIST 1997
metaDesk by Ullmer + Ishii



Tangible User Interface

Coupling of **Bits** and **Atoms**

Users interact with digital information **through a physical form**

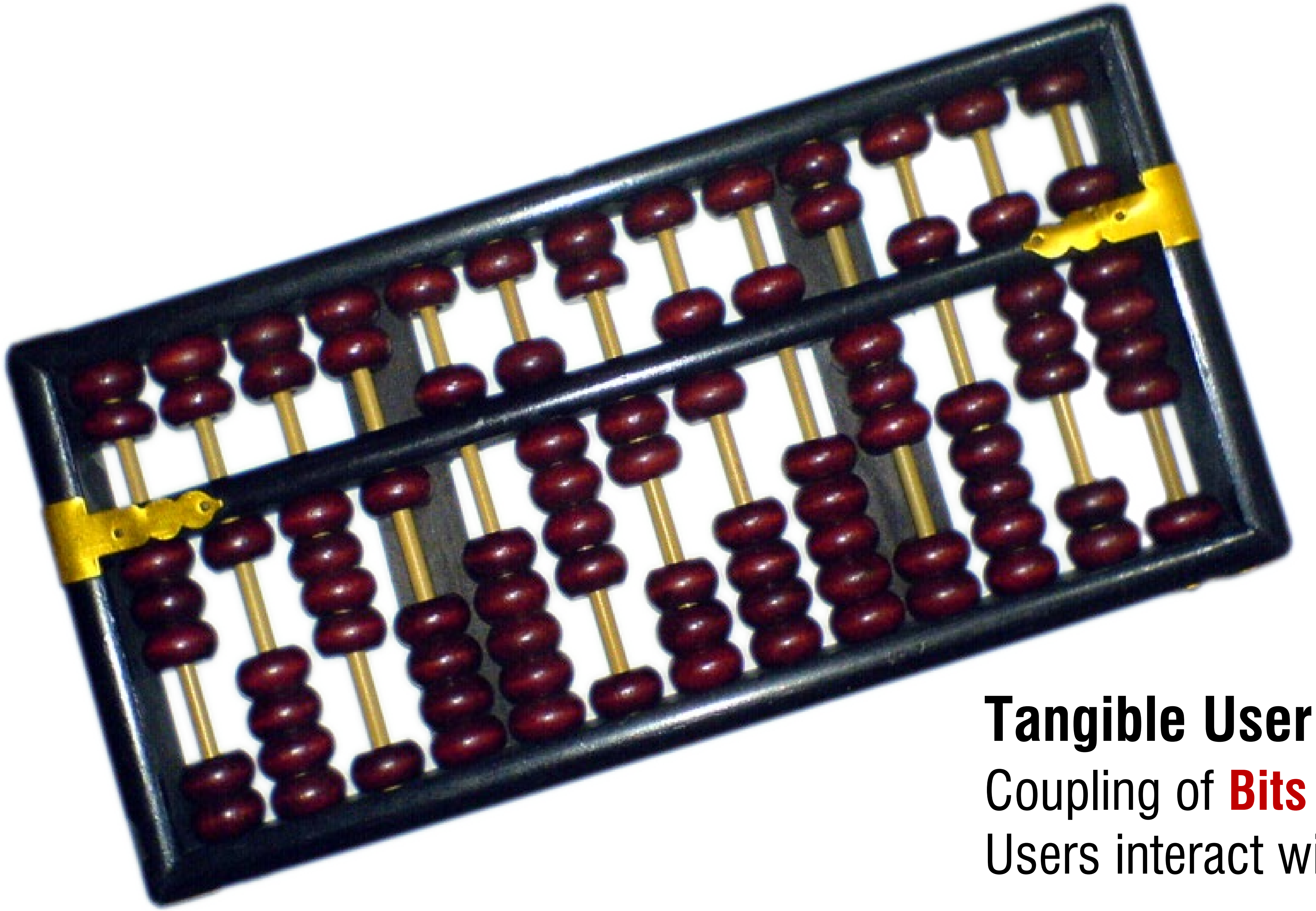
Is this a tangible UI?

No, does not **represent digital information directly**
(it is a generic input device)

Tangible User Interface
Coupling of **Bits** and **Atoms**
Users interact with digital information **through a physical form**

Is the abacus a tangible UI?

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



Ishii met a highly successful PDA (Personal Digital Assistant) called the "abacus" when he was 2 years old. This simple abacus-PDA was not merely a computational device, but also a musical instrument, imaginary toy train, and a back scratcher. He was captivated by the sound and tactile interaction with this simple artifact. When his mother kept household accounts, he was aware of her activities by the sound of her abacus, knowing he could not ask for her to play with him while her abacus made its music. We strongly believe this abacus is suggesting to us a direction for the next generation of HCI.

Tangible User Interface

Coupling of **Bits** and **Atoms**

Users interact with digital information **through a physical form**

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 one of the classic multimedia drawing software programs that

CHI 2004
Kimiko et al.

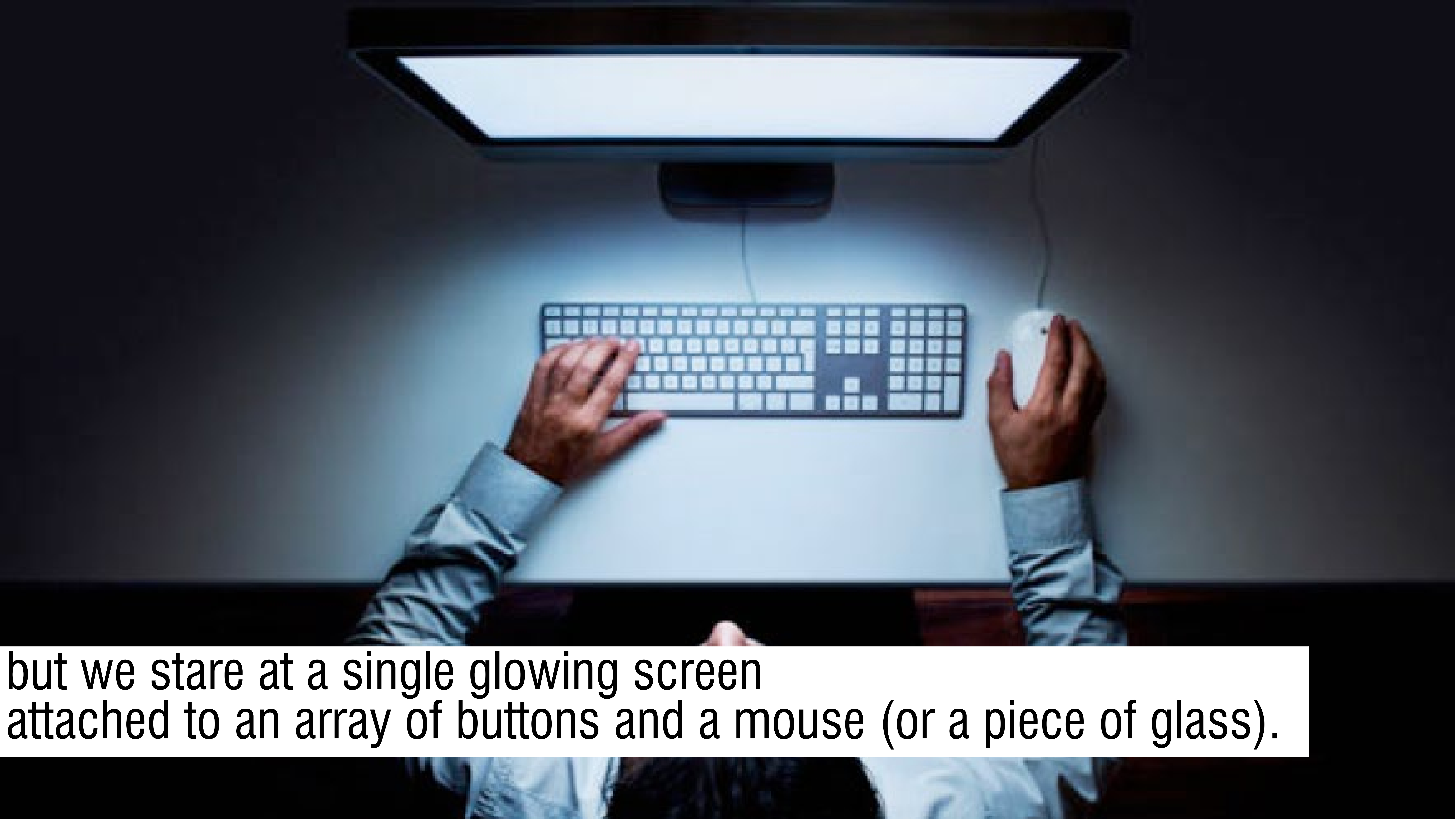
Tangible User Interface

Coupling of **Bits** and **Atoms**

Users interact with digital information **through a physical form**

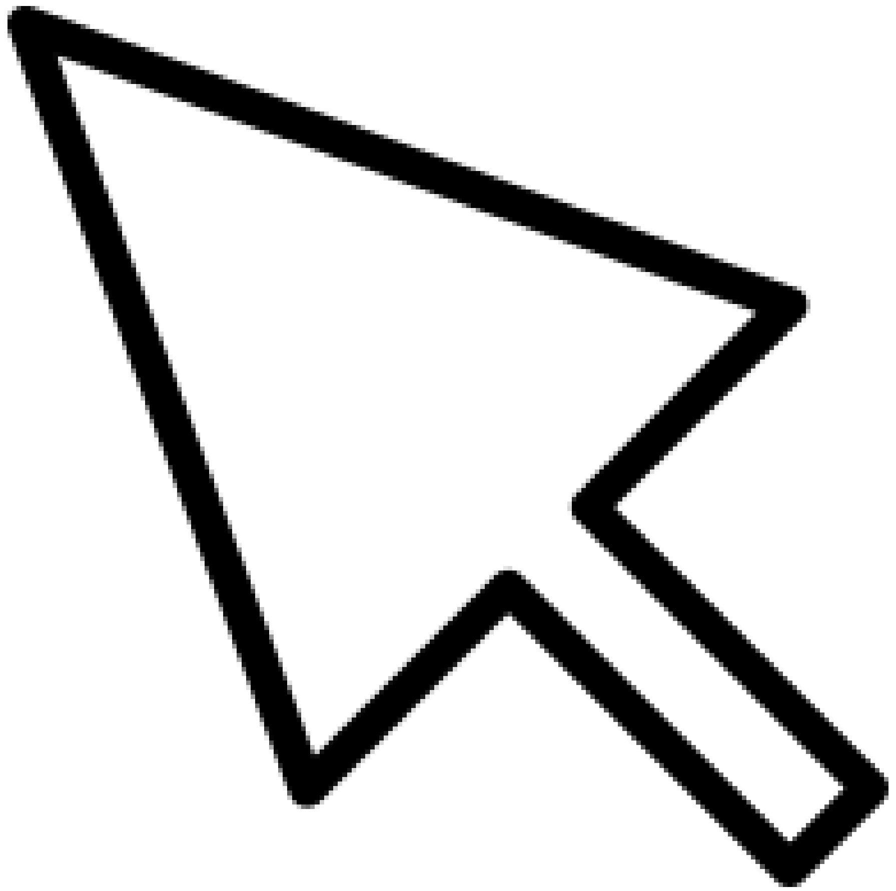
Why tangible?

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



but we stare at a single glowing screen
attached to an array of buttons and a mouse (or a piece of glass).

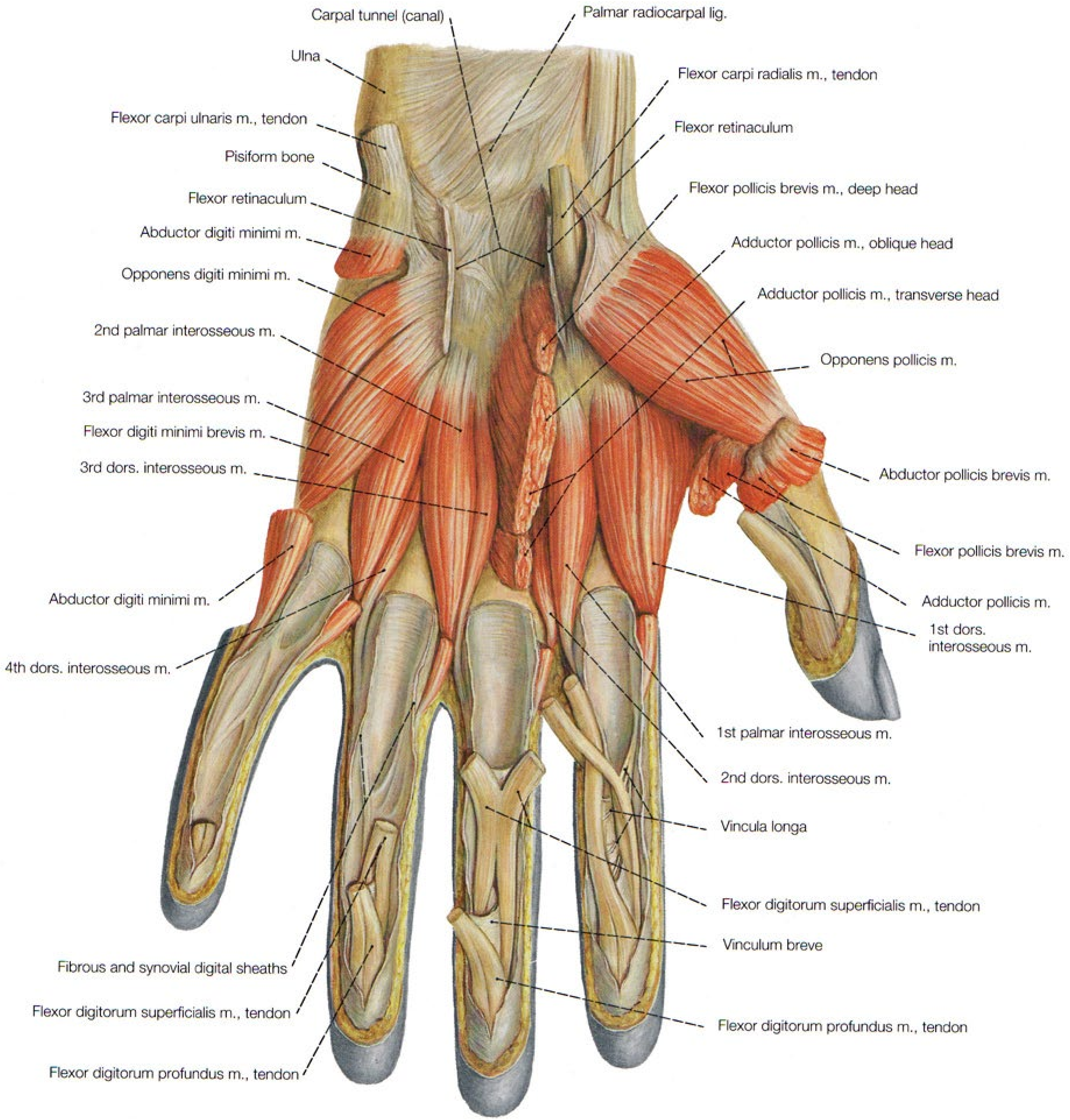
how your computer sees you:



(x,y)

-> very **limited bandwidth** for interaction

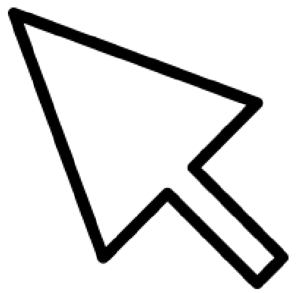
Sensory Homunculus

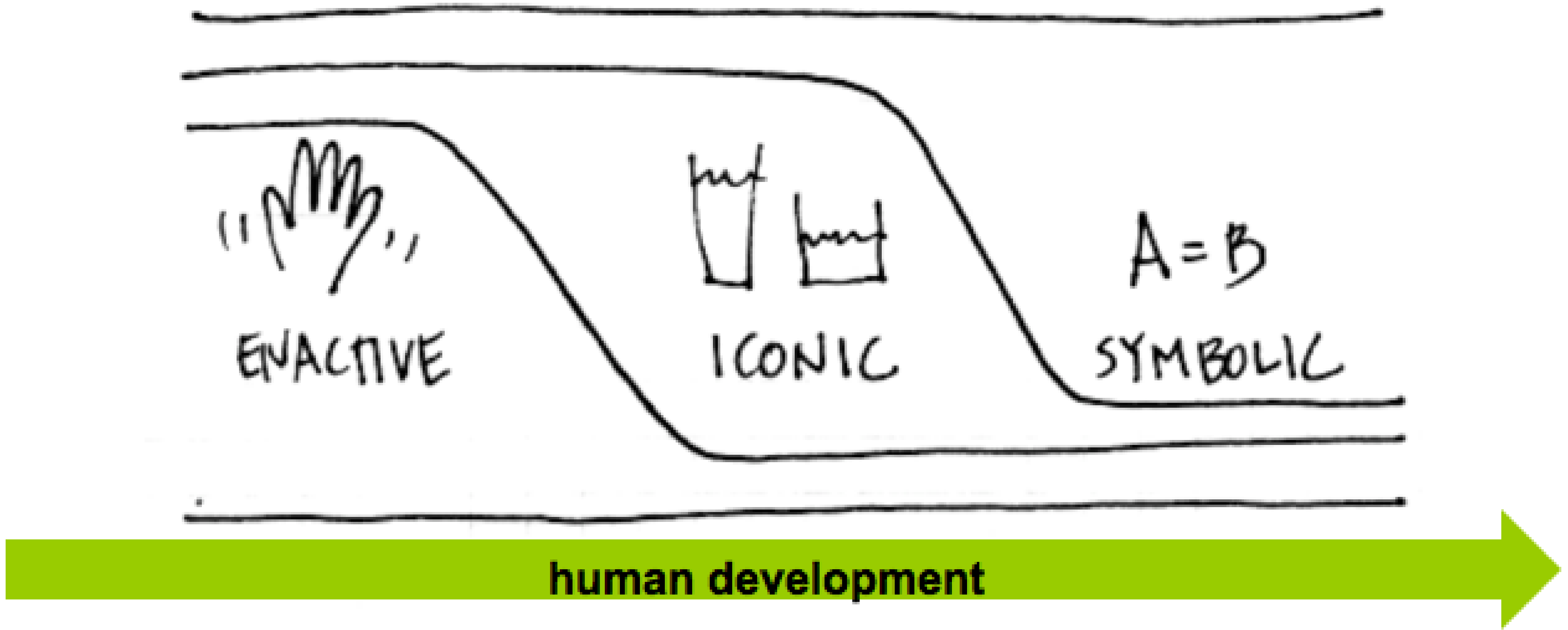

Carpal tunnel (canal)
Palmar radiocarpal lig.
Ulna
Flexor carpi radialis m., tendon
Flexor carpi ulnaris m., tendon
Flexor retinaculum
Pisiform bone
Flexor pollicis brevis m., deep head
Flexor retinaculum
Abductor digiti minimi m.
Adductor pollicis m., oblique head
Opponens digiti minimi m.
Adductor pollicis m., transverse head
2nd palmar interosseous m.
Opponens pollicis m.
3rd palmar interosseous m.
Flexor digiti minimi brevis m.
3rd dors. interosseous m.
Abductor pollicis brevis m.
Flexor pollicis brevis m.
Abductor digiti minimi m.
Adductor pollicis m.
1st dors. interosseous m.
4th dors. interosseous m.
1st palmar interosseous m.
2nd dors. interosseous m.
Vincula longa
Flexor digitorum superficialis m., tendon
Vinculum breve
Fibrous and synovial digital sheaths
Flexor digitorum superficialis m., tendon
Flexor digitorum profundus m., tendon
Flexor digitorum profundus m., tendon

CHI1995
Fitzmaurice et.al.

Tangible UI:

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

not like  (x,y) but with full bandwidth

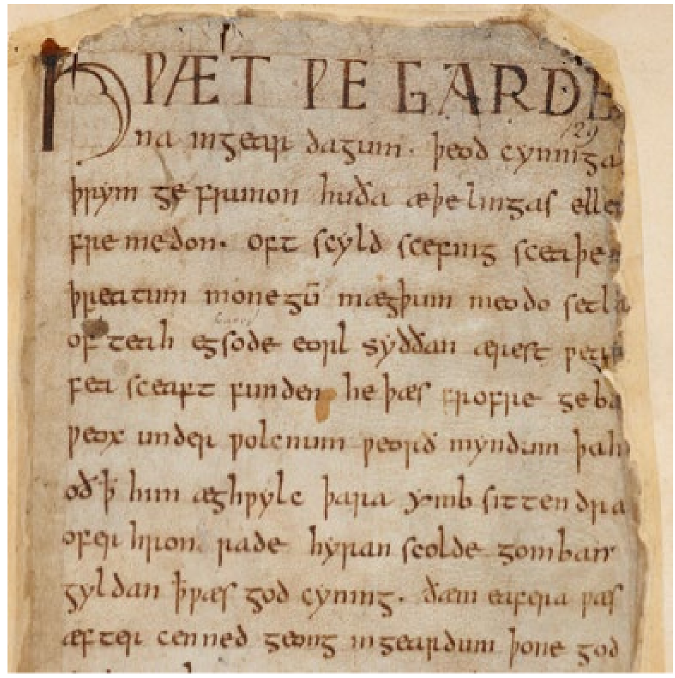


actions

representing a result

images

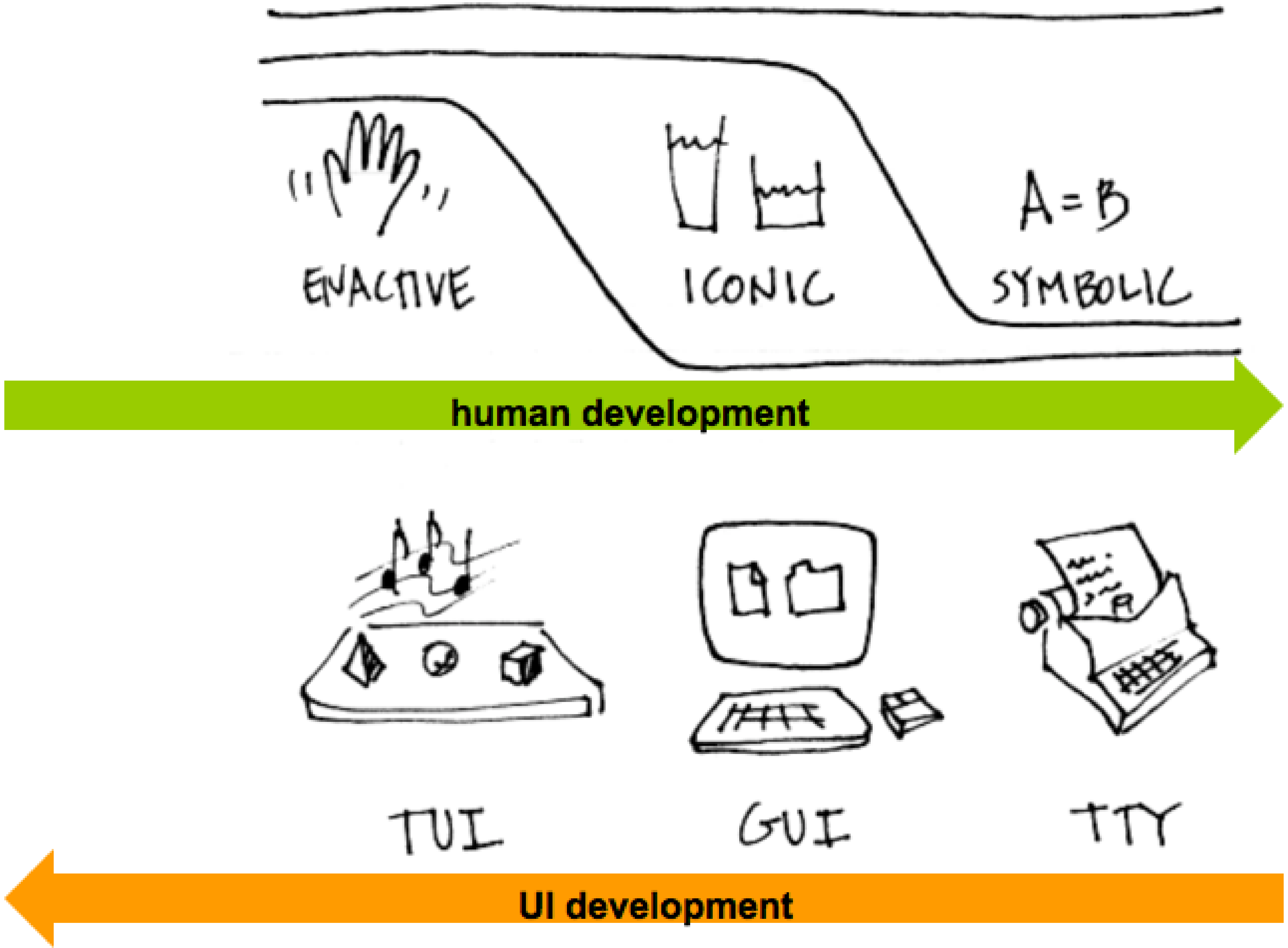
representing a concept



symbolic

describing the concept

Interaction Design Sketchbook [Verplank '09]

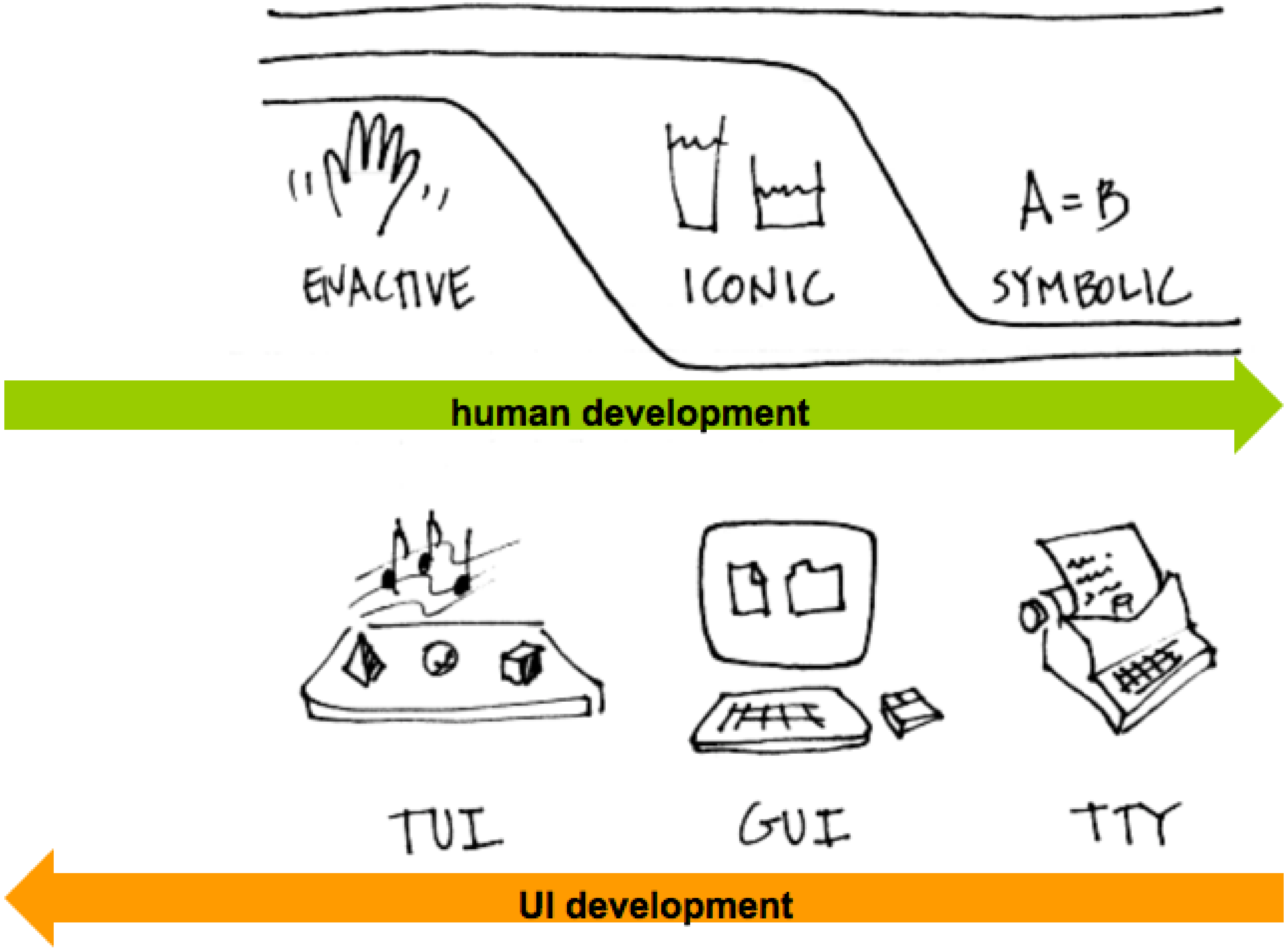


Interaction Design Sketchbook [Verplank ‘09]

symbolic came first: command line interfaces

iconic: graphical user interfaces with desktop metaphor

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



Interaction Design Sketchbook [Verplank '09]

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
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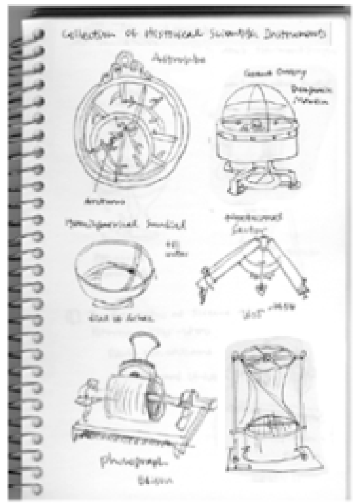

Figure 1 Sketches made at Collection of Historical Scientific Instruments at Harvard University

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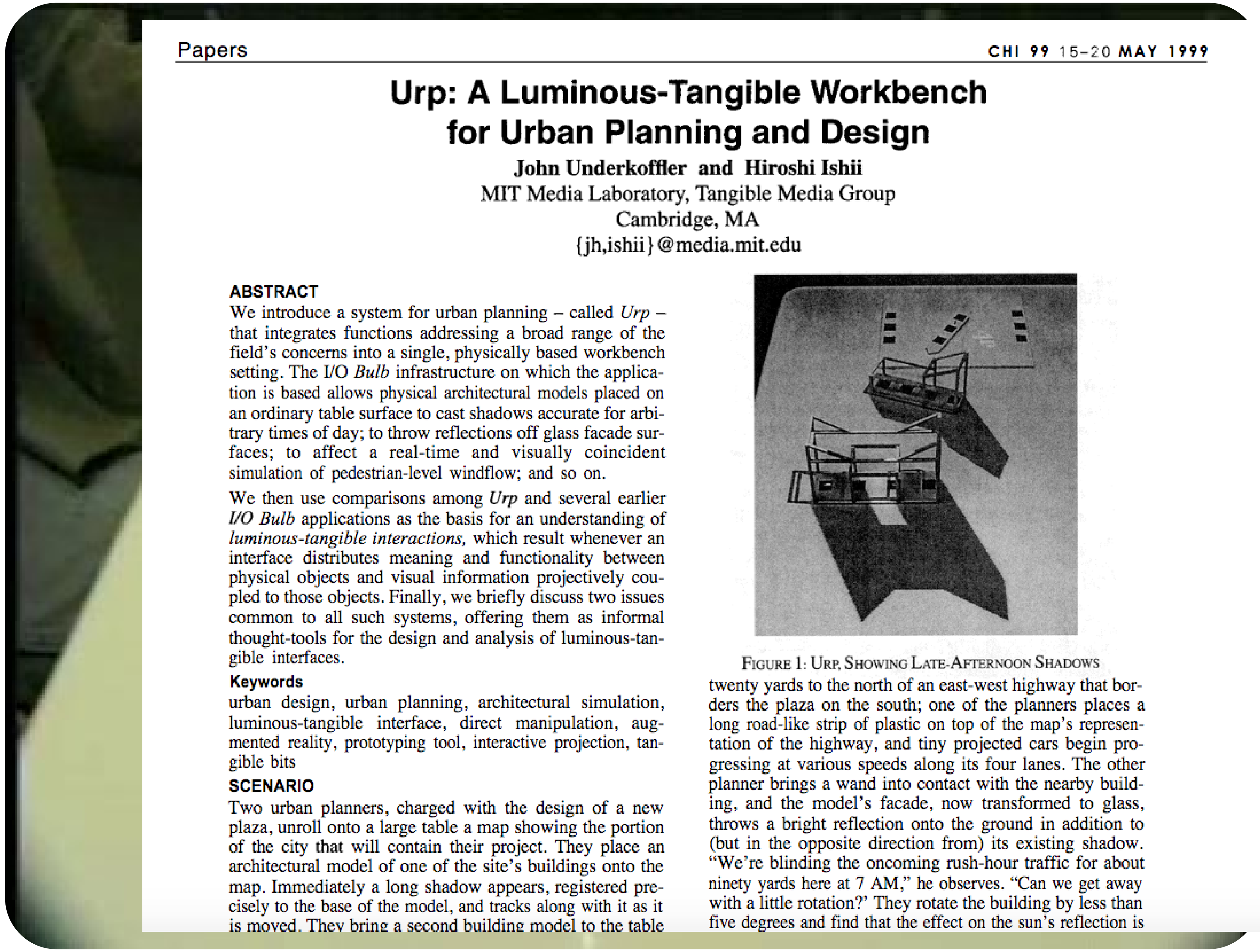
Coupling of **Bits** and **Atoms**

What kind of information/scenario is suitable for tangible interface?

Many early ideas start with coupling digital information with physical tokens on a computational desktop

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 is moved. They bring a second building model to the table

FIGURE 1: URP, SHOWING LATE-AFTERNOON SHADOWS

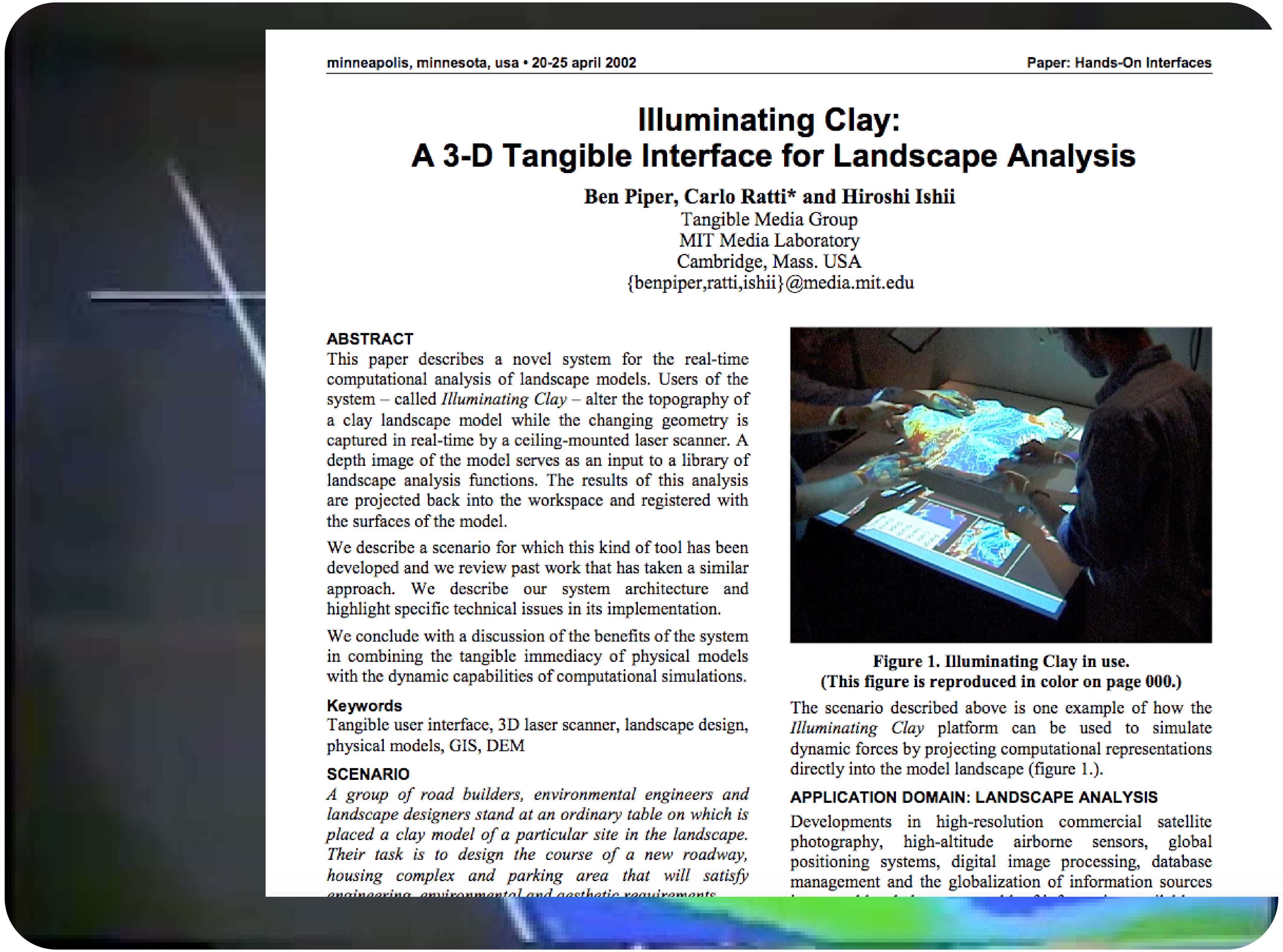
twenty yards to the north of an east-west highway that borders the plaza on the south; one of the planners places a long road-like strip of plastic on top of the map's representation of the highway, and tiny projected cars begin progressing at various speeds along its four lanes. The other planner brings 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 five degrees and find that the effect on the sun's reflection is

1999: John Underkoffler and Ishii

3D Shape and geometry representation

The physical clay model conveys spatial relationships that can be intuitively and directly manipulated by the user's hands --- quickly create and understand highly complex topologies

The user is free to use any object, material or form to interface with the computer



minneapolis, minnesota, usa • 20-25 april 2002 | Paper: Hands-On Interfaces

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, housing complex and parking area that will satisfy

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 management and the globalization of information sources

2002: Ben Piper and Hiroshi Ishii: Illuminating Clay

Physical tokens later became active

CurlyBot

Published in the Proceedings of CHI 2000, April 1-6, 2000, ACM Press, ©2000 ACM

curlybot: Designing a New Class of Computational Toys

Phil Frei, Victor Su, Bakhtiar Mikhak*, and Hiroshi Ishii
Tangible Media Group
*Epistemology and Learning Group
MIT Media Laboratory
20 Ames Street
Cambridge, MA 02139
+1 617.253.9401
{frei, vsu, mikhak, ishii}@media.mit.edu

ABSTRACT
We introduce an educational toy, called *curlybot*, as the basis for a new class of toys aimed at children in their early stages of development – ages four and up. *curlybot* is an autonomous two-wheeled vehicle with embedded electronics that can record how it has been moved on any flat surface and then play back that motion accurately and repeatedly. Children can use *curlybot* to develop intuitions for advanced mathematical and computational concepts, like differential geometry, through play away from a traditional computer.

In our preliminary studies, we found that children learn to use *curlybot* quickly. They readily establish an affective and body syntonic connection with *curlybot*, because of its ability to remember all of the intricacies of their original gesture; every pause, acceleration, and even the shaking in their hand is recorded. Programming by example in this context makes the educational ideas implicit in the design of *curlybot* accessible to young children.

Keywords
Education, learning, children, tangible interface, toy

INTRODUCTION

The role of physical objects in the development of young children has been studied extensively in the past. In particular, it has been shown that a careful choice of materials can enhance children's learning. A particularly notable example of such materials is Friedrich Froebel's collection of twenty physical objects (so called "gifts"), each designed with the purpose of making a particular concept accessible to and manipulable by children [5]. The presence of objects inspired by Froebel in almost all kindergartens today is a reflection of their recognized value in the development of young children.

Figure 1: Three palm-sized *curlybots* (each with a large record/playback button and a small indicator light).

Most recently, Mitchel Resnick and his Lifelong Kindergarten Group at the MIT Media Laboratory have introduced a collection of digital manipulatives that builds on Froebel's work, taking full advantage of computational ideas and resources not available until recently [12,14]. Much like Froebel's gifts, these tools attempt to make new domains of knowledge accessible to children.

In this paper, we contribute to this initiative a new class of computational toys that is aimed at children as young as four. *curlybot*, the first instantiation and the basis of this class of toys, is a two-wheeled toy that can record and play back physical motion replicating every intricacy of the original motion. It is a smooth, easily graspable curved object with a button and an LED for indicating whether the device is in record (red) or playback (green) mode. To record a gesture, a child presses the button and moves *curlybot* through a desired path. A child presses the button a second time, to stop recording and begin playback of the recorded gesture. The playback mode repeats the gesture indefinitely until the button is pressed again. Because of the simplicity of the interface, children quickly learn to create intricate gestures with *curlybot*, which they can refine through an iterative process.

1999: Frei et.al

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.

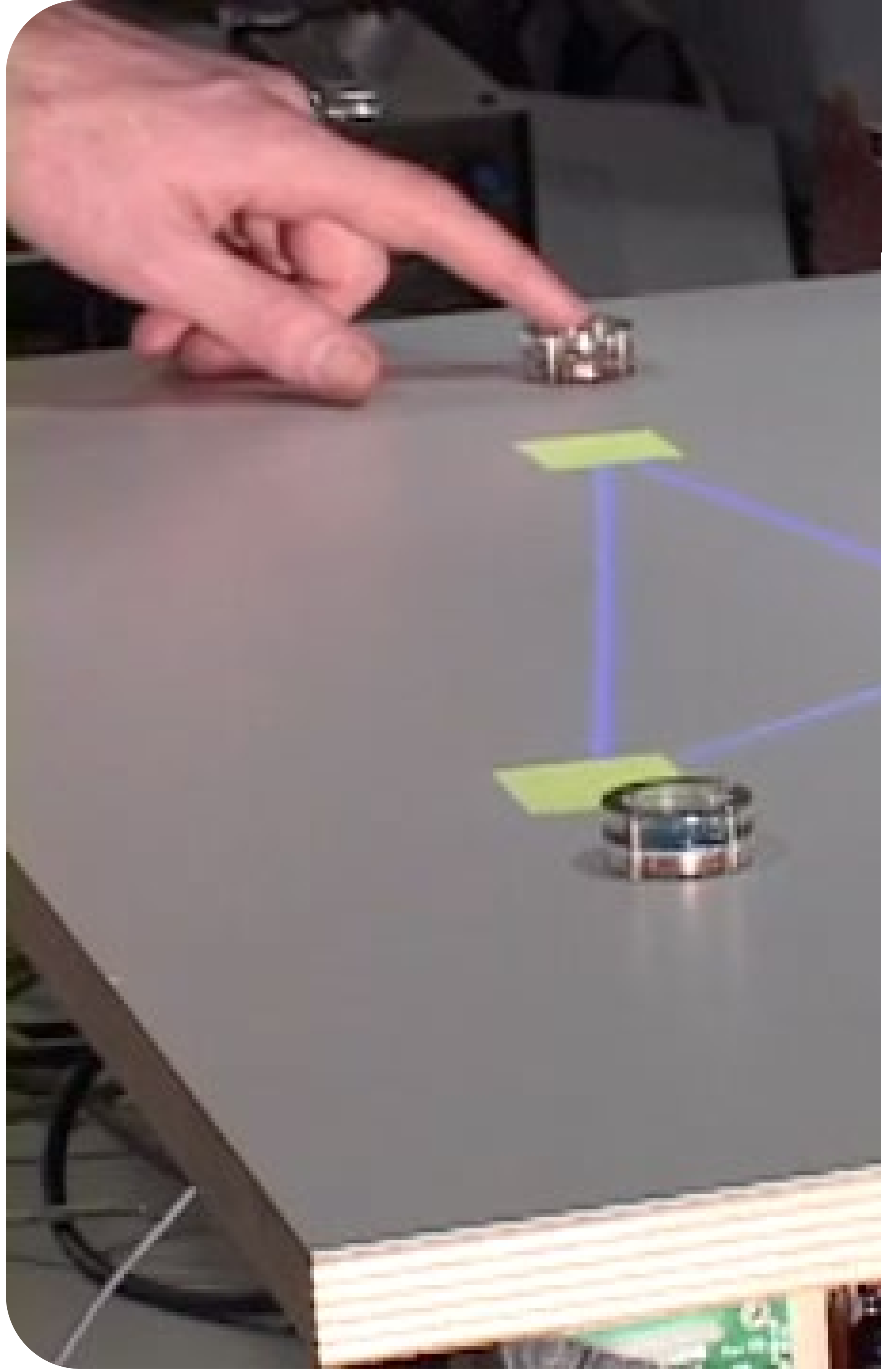
KEYWORDS: Tangible user interfaces, physical interaction, actuation, synchronization, interactive surface, object tracking, computer supported cooperative work.

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 organize objects spatially to aid problem solving, the

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 reflected in a physical change of its associated object. With

2002: Pangaro: Actuated Workbench



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

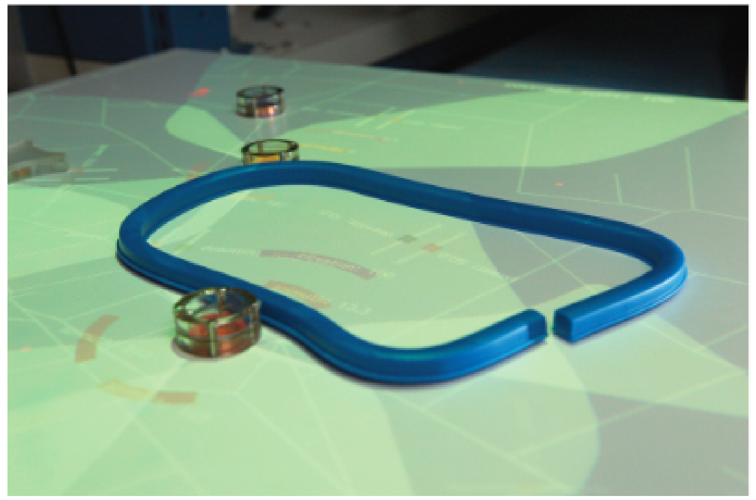


Figure 1: A flexible "artist's curve" constraining the motion of a cellphone tower in the Pico system.

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

2007: Patten: physical constraints influence computation

Zooids: Building Blocks for Swarm User Interfaces

Mathieu Le Goc[1,3,4], Lawrence H. Kim[2], Ali Parsaei[2], Jean-Daniel Fekete[1,4] Pierre Dragicevic[1,4], Sean Follmer[2]

[1]Inria, [2]Stanford University, [3]Université Paris-Sud, [4]Université Paris-Saclay

{mathieu.le-goc, pierre.dragicevic, jean-daniel.fekete}@inria.fr, {lawkim, aparsaei, sfollmer}@stanford.edu

Figure 1. ***Zooids*** **can be held as tokens, manipulated collectively or individually, behave as physical pixels, act as handles and controllers, and can move dynamically under machine control. They are building blocks for a new class of user interface we call** ***swarm user interfaces*****.**

ABSTRACT

This paper introduces *swarm user interfaces*, a new class of human-computer interfaces comprised of many autonomous robots that handle both display and interaction. We describe the design of *Zooids*, an open-source open-hardware platform for developing tabletop swarm interfaces. The platform consists of a collection of custom-designed wheeled micro robots each 2.6 cm in diameter, a radio base-station, a high-speed DLP structured light projector for optical tracking, and a software framework for application development and control. We illustrate the potential of tabletop swarm user interfaces through a set of application scenarios developed with Zooids, and discuss general design considerations unique to swarm user interfaces.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

interact with *"a new kind of matter capable of changing form dynamically"* [26].

Several significant steps have been recently made towards Sutherland's and Ishii's visions, particularly through research on actuated tangibles [48, 50, 78] and shape displays [55, 56, 15]. However, current systems suffer from a number of limitations. First, actuated tabletop tangibles generally only support the manipulation and actuation of a few (e.g., 3–4) solid objects, which is not enough to emulate physical matter that can change form. On the other hand, shape displays try to achieve surfaces that can be deformed and actuated, but current implementations do not support arbitrary physical topologies. Furthermore, both types of systems traditionally use physical objects primarily as *input*, while *output* is almost always provided through separate pixel-based display technology. Although video-projected overlays allows input and output to spatially coincide [12], they provide only a limited sense of physicality [5]. Likewise, many such systems require heavy

UIST 2016

Goc et al.

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.

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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 revolving based on simulated physical conditions. We describe the technology, interaction scenarios and challenges, dis-

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 surfaces [5][4]. In these scenarios input can be sensed in the 3D physical space, but the objects and rendered

CHI 2012
Lee et al.

What is missing in Tangible Bits?

Physical atoms are not as “flexible” as digital bits

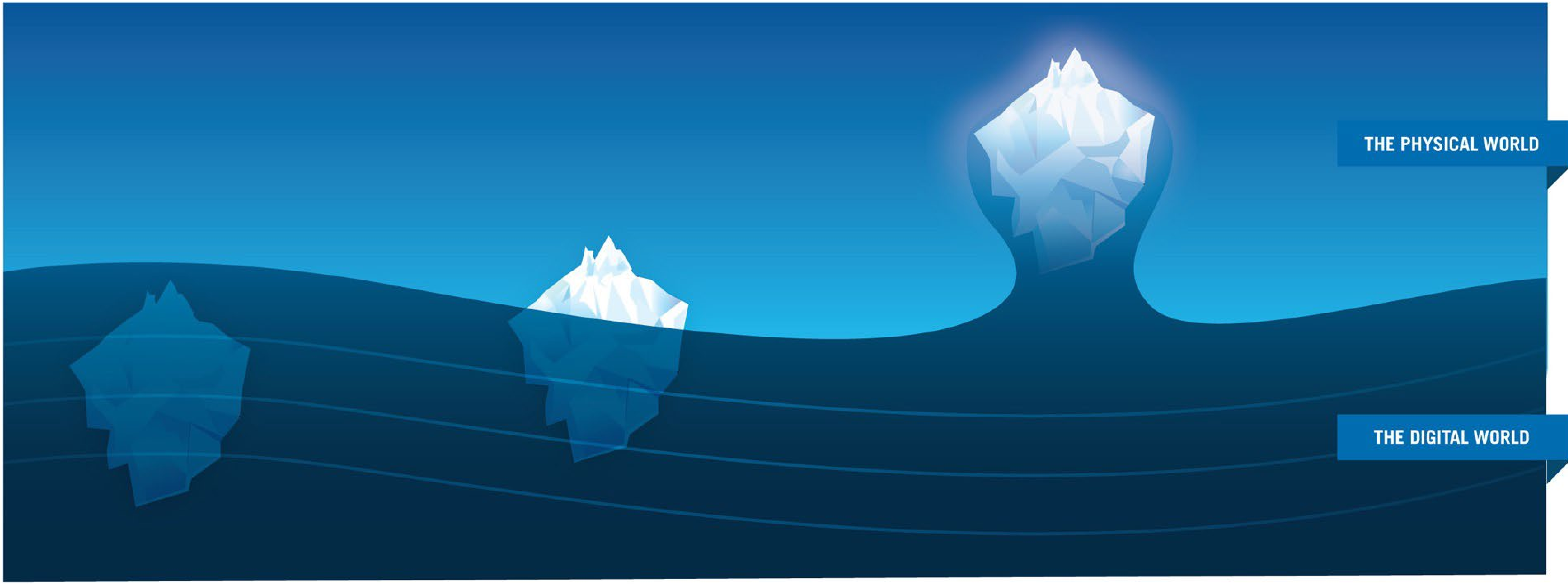
“active” physical interface?

Physical atoms are not as “flexible” as digital bits

GUI PAINTED BITS

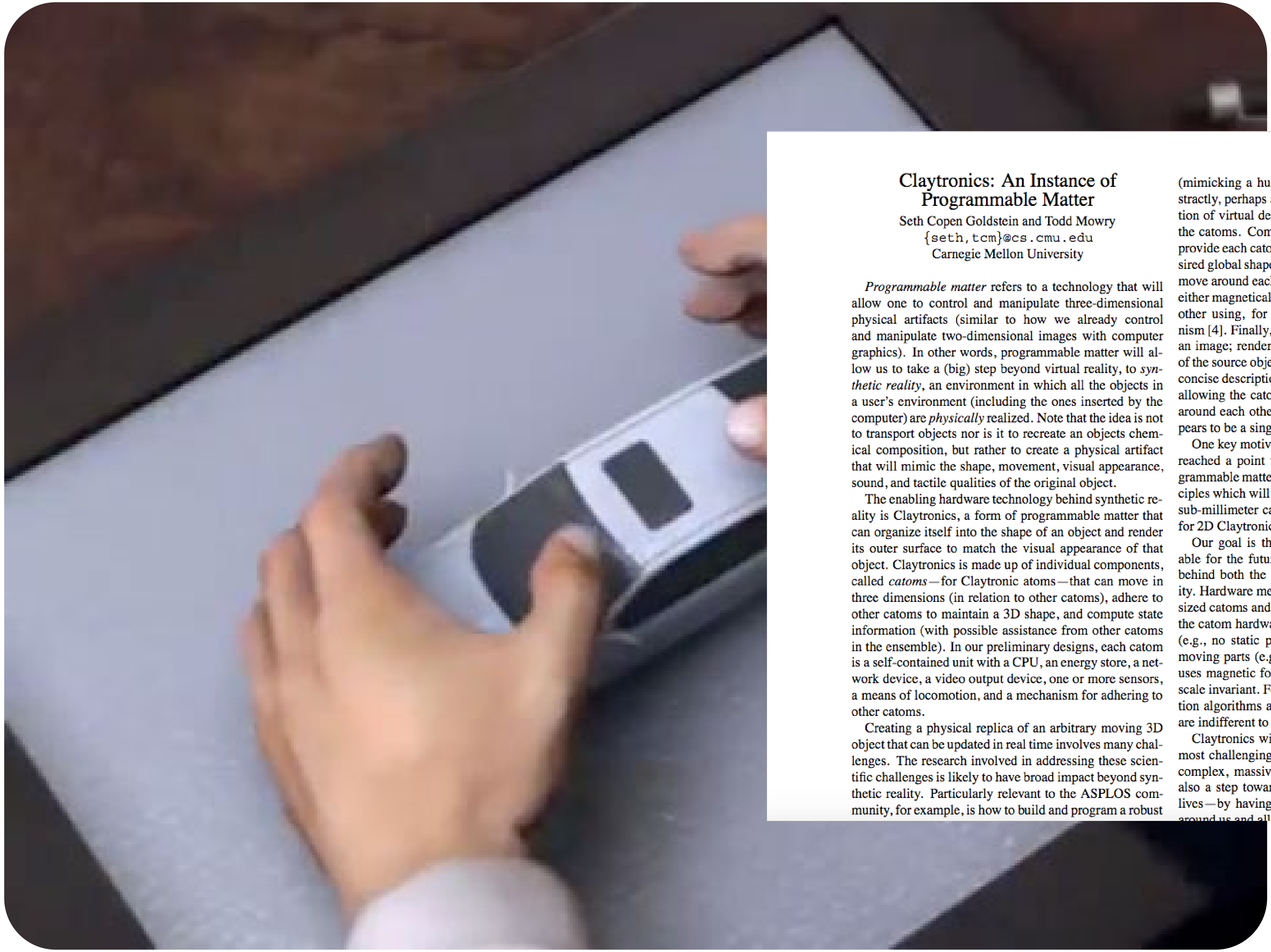
TUI TANGIBLE BITS

RADICAL ATOMS



2012: Hiroshi Ishii’s vision: Radical Atoms

Radical Atoms goes beyond Tangible Bits by assuming a hypothetical generation of materials that can change form and appearance dynamically, becoming as reconfigurable as pixels on a screen.



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.

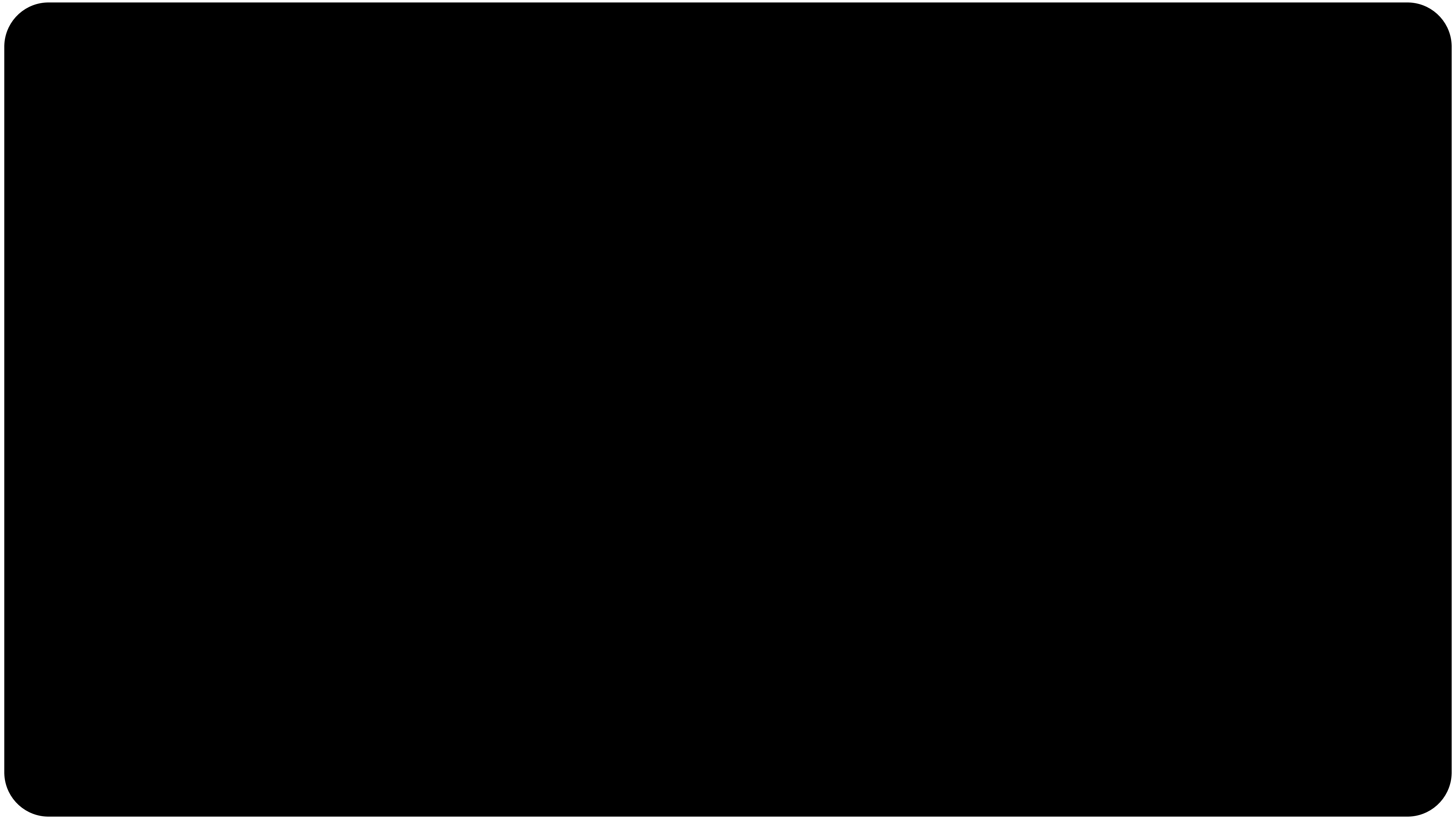
Creating a physical replica of an arbitrary moving 3D object that can be updated in real time involves many challenges. The research involved in addressing these scientific challenges is likely to have broad impact beyond synthetic reality. Particularly relevant to the ASPLOS community, for example, is how to build and program a robust (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.

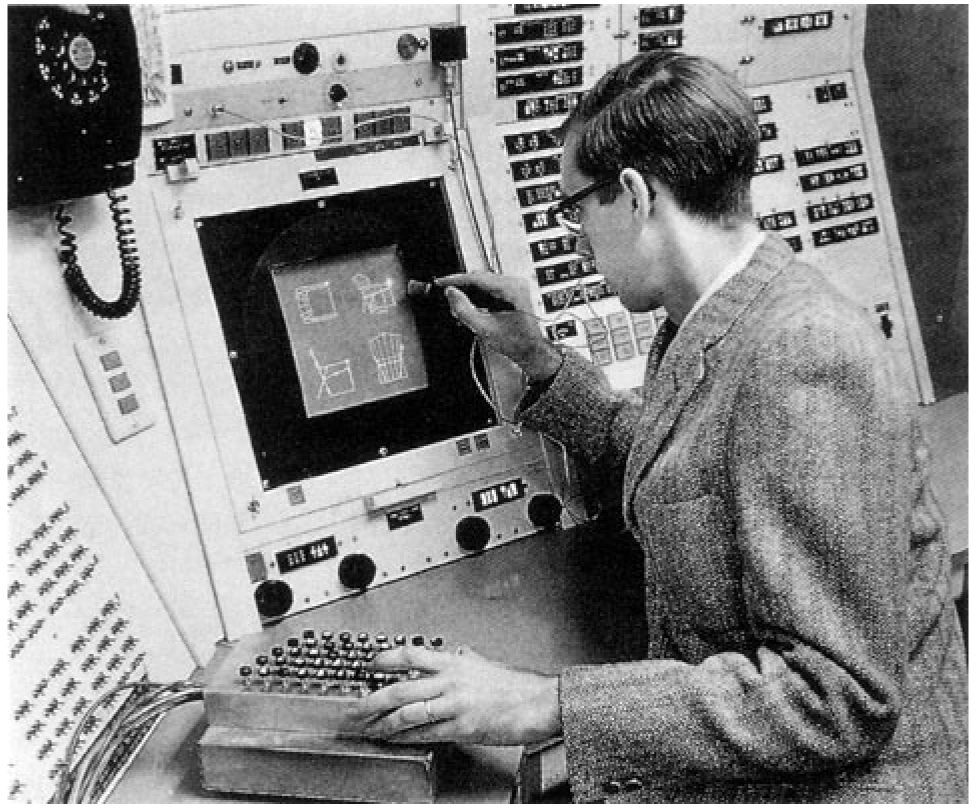
Claytronics will be a test-bed for solving some of the most challenging problems we face today: how to build complex, massively distributed dynamic systems. It is also a step towards truly integrating computers into our lives—by having them integrated into the very artifacts around us and allowing them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

2004: Claytronics vision (not implemented)



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

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



ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces

Ken Nakagaki[1], Artem Dementyev[1], Sean Follmer[2], Joseph A. Paradiso[1], Hiroshi Ishii[1]

[1]MIT Media Lab
Cambridge, MA
{ken_n, artemd, joep, ishii}@media.mit.edu

[2]Stanford University
Stanford, CA
sfollmer@stanford.edu

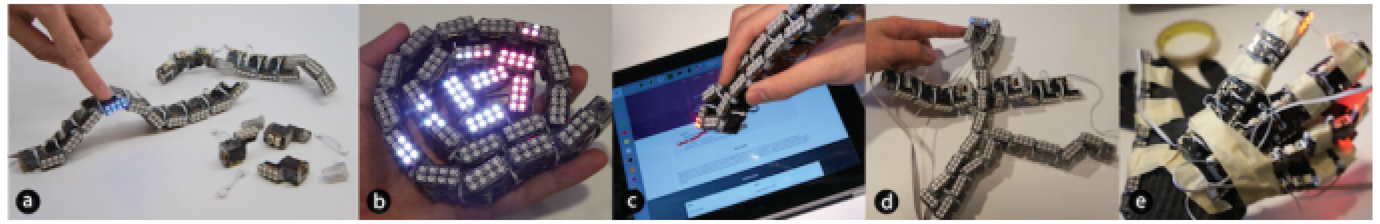


Figure 1. Device and application examples of the ChainFORM hardware system. (a: ChainFORM hardware configurations and modules, b: reconfigurable display, c: shape changing stylus, d: animated character, e: haptic glove.)

ABSTRACT

This paper presents ChainFORM: a linear, modular, actuated hardware system as a novel type of shape changing interface. Using rich sensing and actuation capability, this modular hardware system allows users to construct and customize a wide range of interactive applications. Inspired by modular and serpentine robotics, our prototype comprises identical modules that connect in a chain. Modules are equipped with rich input and output capability: touch detection on multiple surfaces, angular detection, visual output, and motor actuation. Each module includes a servo motor wrapped with a flexible circuit board with an embedded microcontroller.

Leveraging the modular functionality, we introduce novel interaction capability with shape changing interfaces, such as rearranging the shape/configuration and attaching to passive objects and bodies. To demonstrate the capability and interaction design space of ChainFORM, we implemented a variety of applications for both computer interfaces and hands-on prototyping tools.

Author Keywords

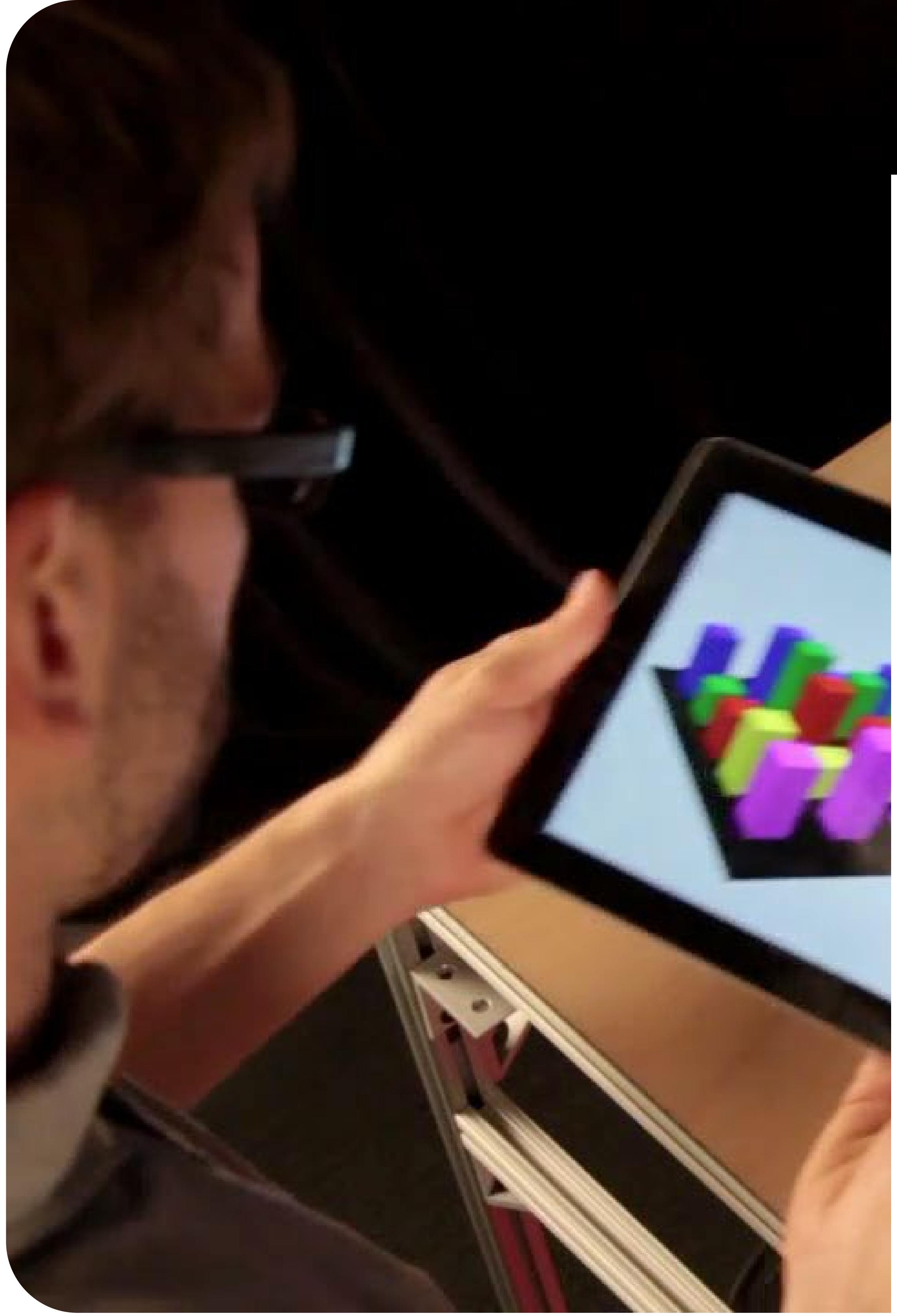
Actuated Curve Interfaces; Shape Changing Interfaces; Modular Robotics

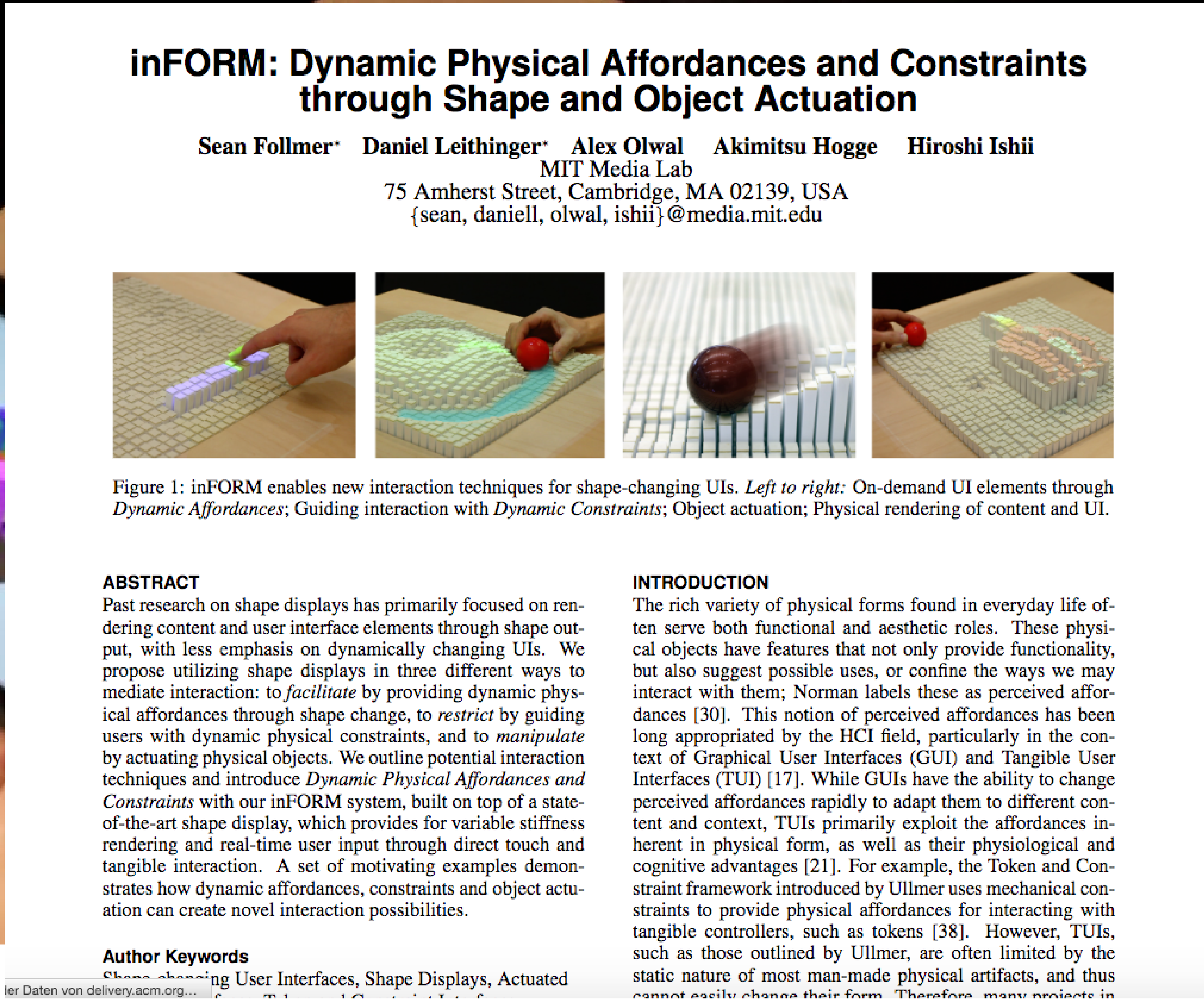
INTRODUCTION

As shape changing interfaces being an emerging field in HCI, a lot of actuation techniques have been introduced to provide physical shapes to represent digital data and to embody spatial interactions [9, 4]. Researchers are continually seeking techniques that have a variety of transformational capabilities in different geometries and scales [14, 24]. To extend the sensing and display capability of such shape changing interfaces, extra sensors or cameras and projectors have been installed for detecting human input and displaying information on the active surfaces. However, this strategy poses a challenge for scaling the system, which presents a problem, especially for mobile applications. To push the boundaries of shape-changing interface research, another approach calls for self-contained systems that integrate sensing, actuation and display across different scales, geometries, and transformations.

We present ChainFORM: a modular integrated hardware system that has a chained, linear form factor (Figure 1). The hardware comprises identical actuated modules connected in series, which allows the user to customize the length and the configuration of devices they construct. The form-factor of line and the modularity expands the possibility of transformation for both shapes and scales. In addition, each module inte-

UIST 2016: Nakagaki et.al.





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

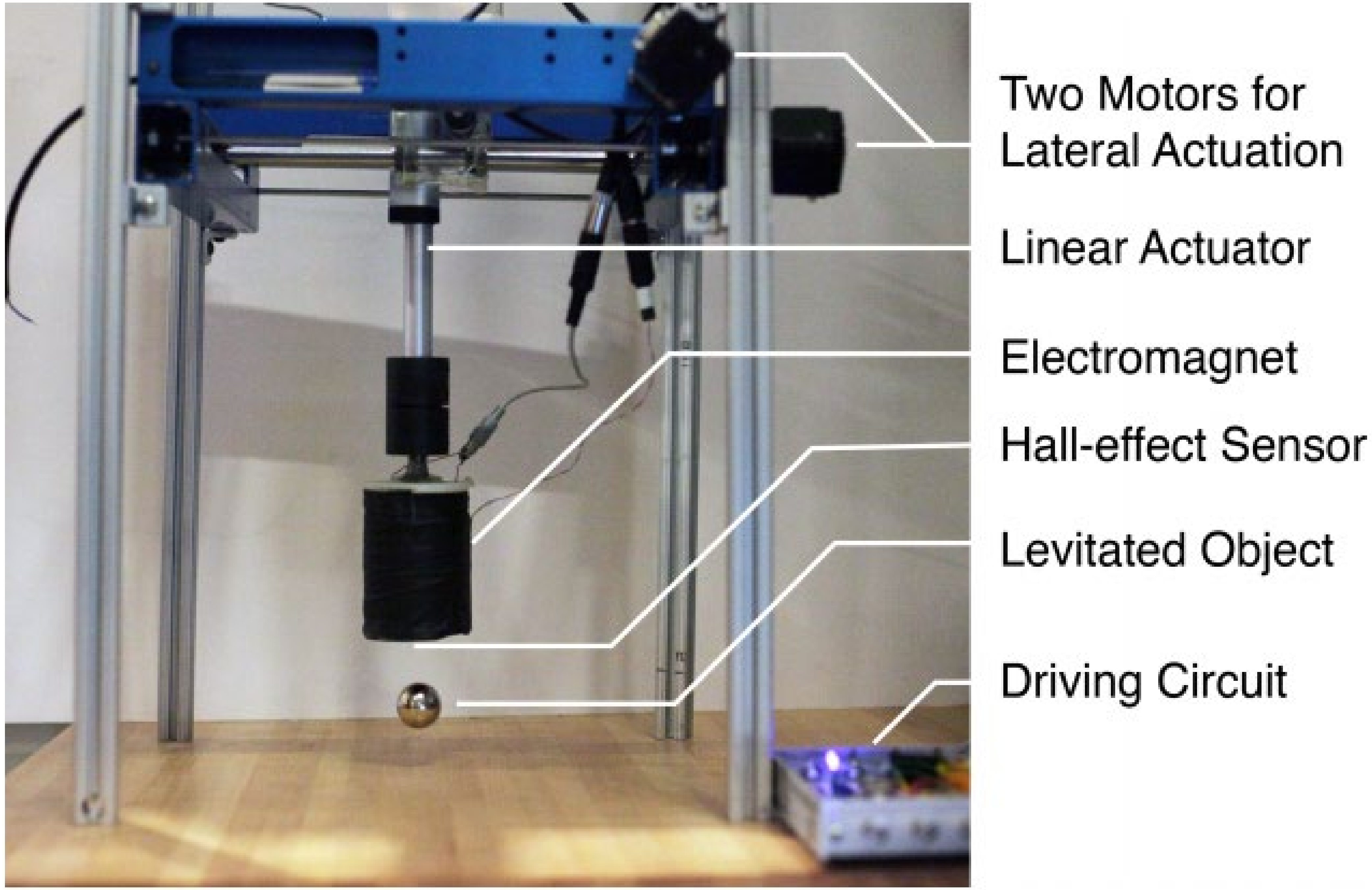
Shape-changing User Interfaces, Shape Displays, Actuated

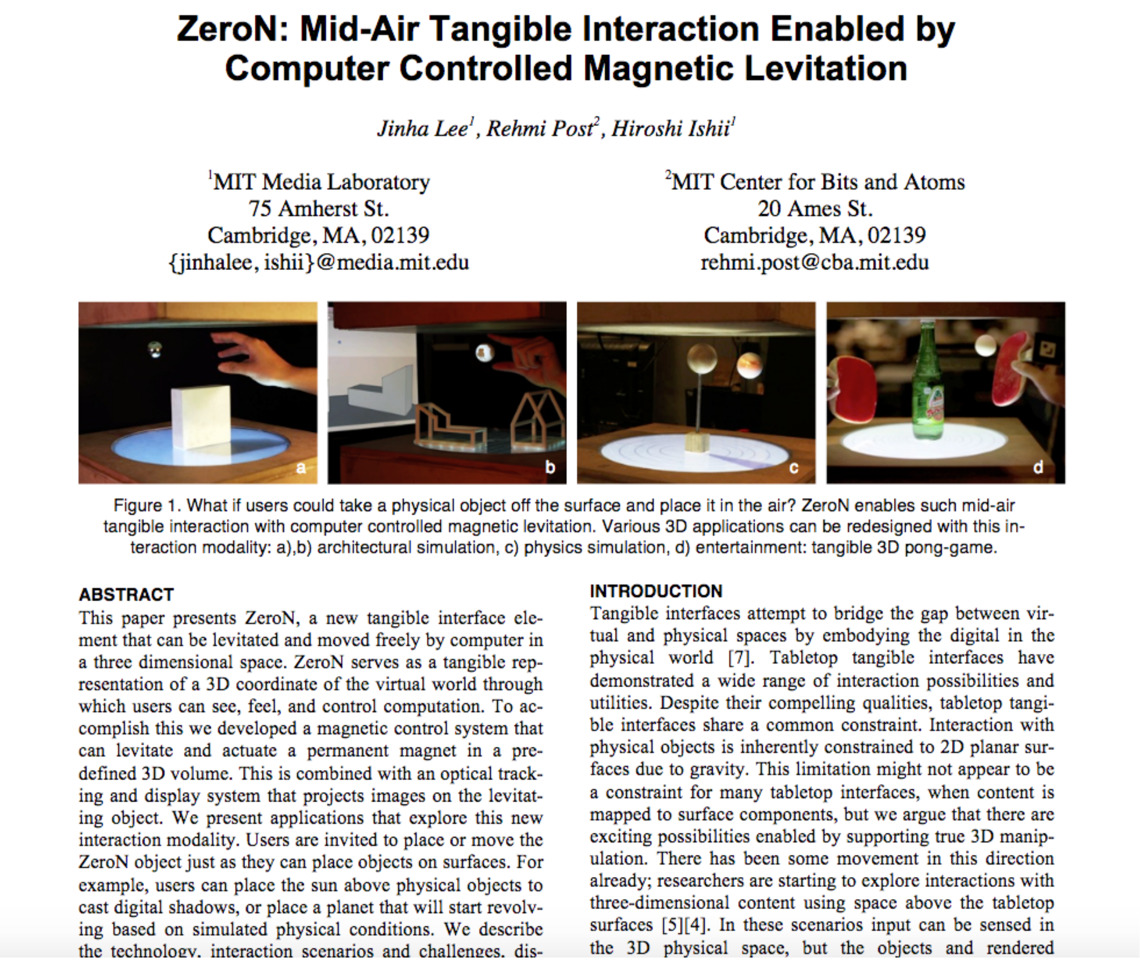
INTRODUCTION

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 static nature of most man-made physical artifacts, and thus

2013: Leithinger, Ishii: inForm shape display

Some of the key technologies





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

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

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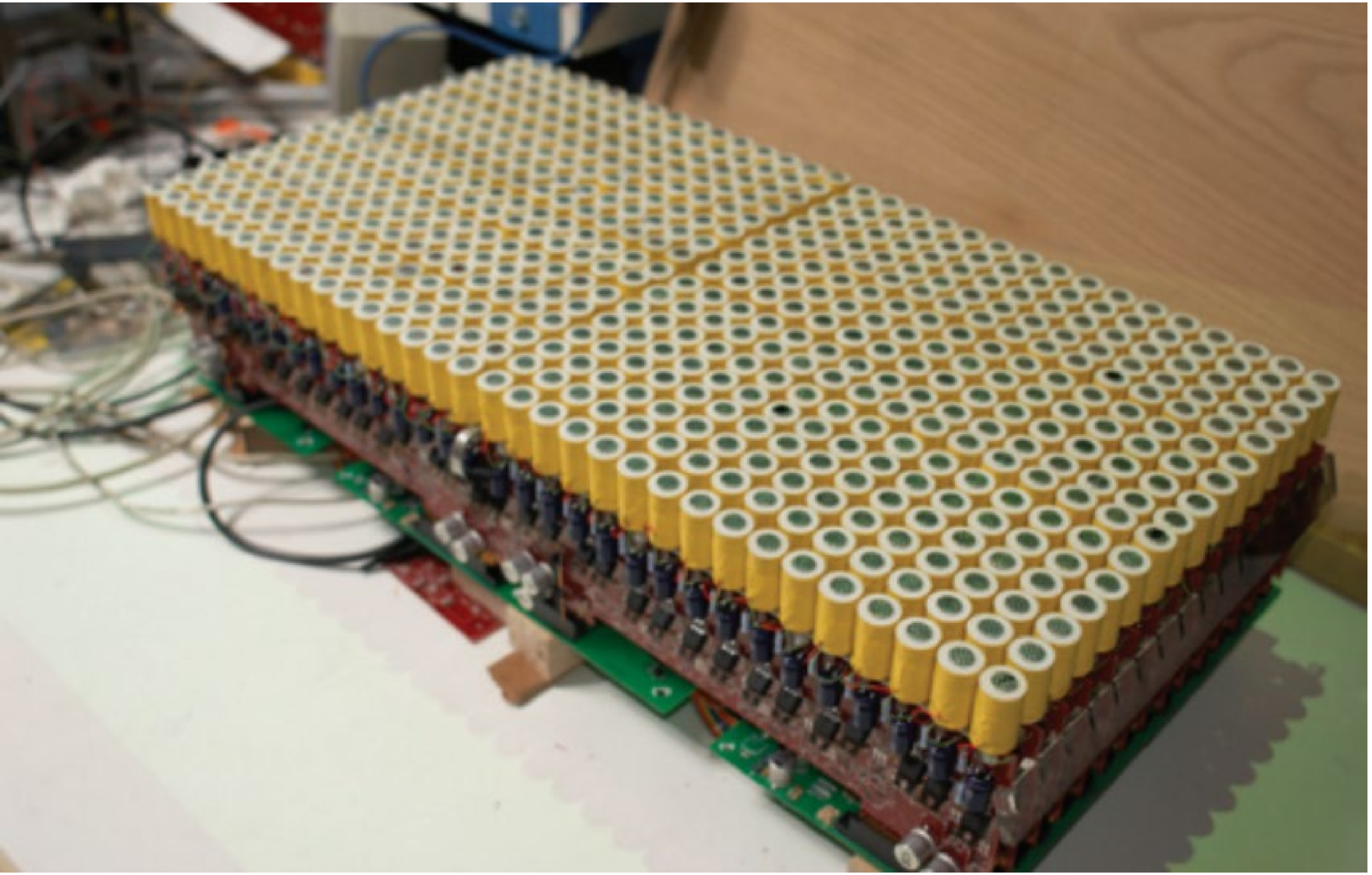
CHI 2012
Lee et al.



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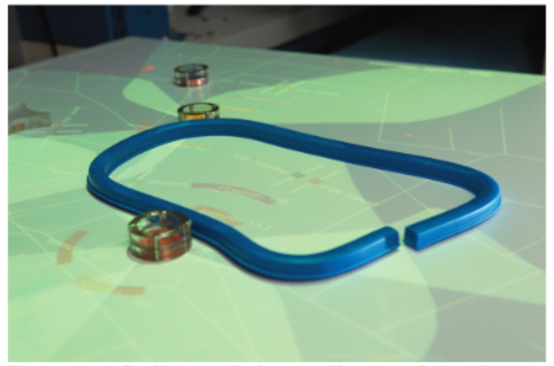

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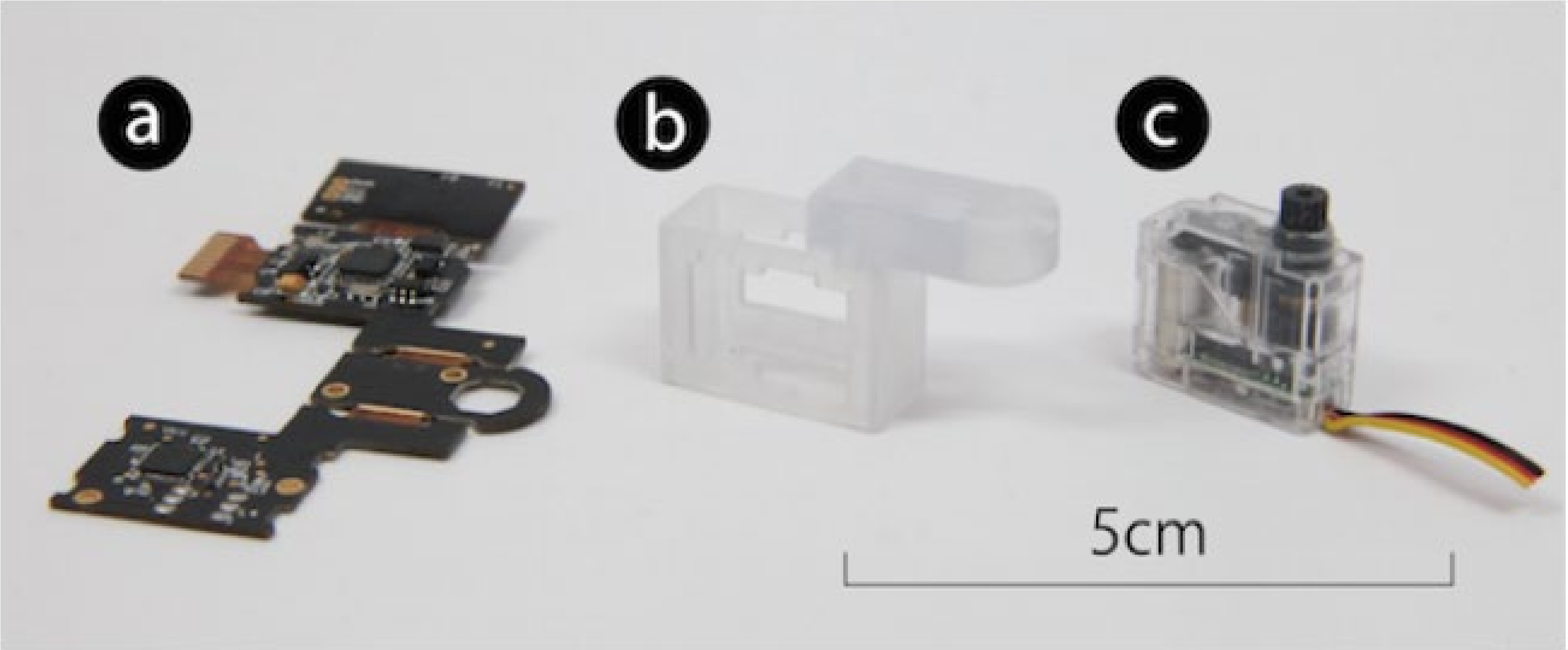
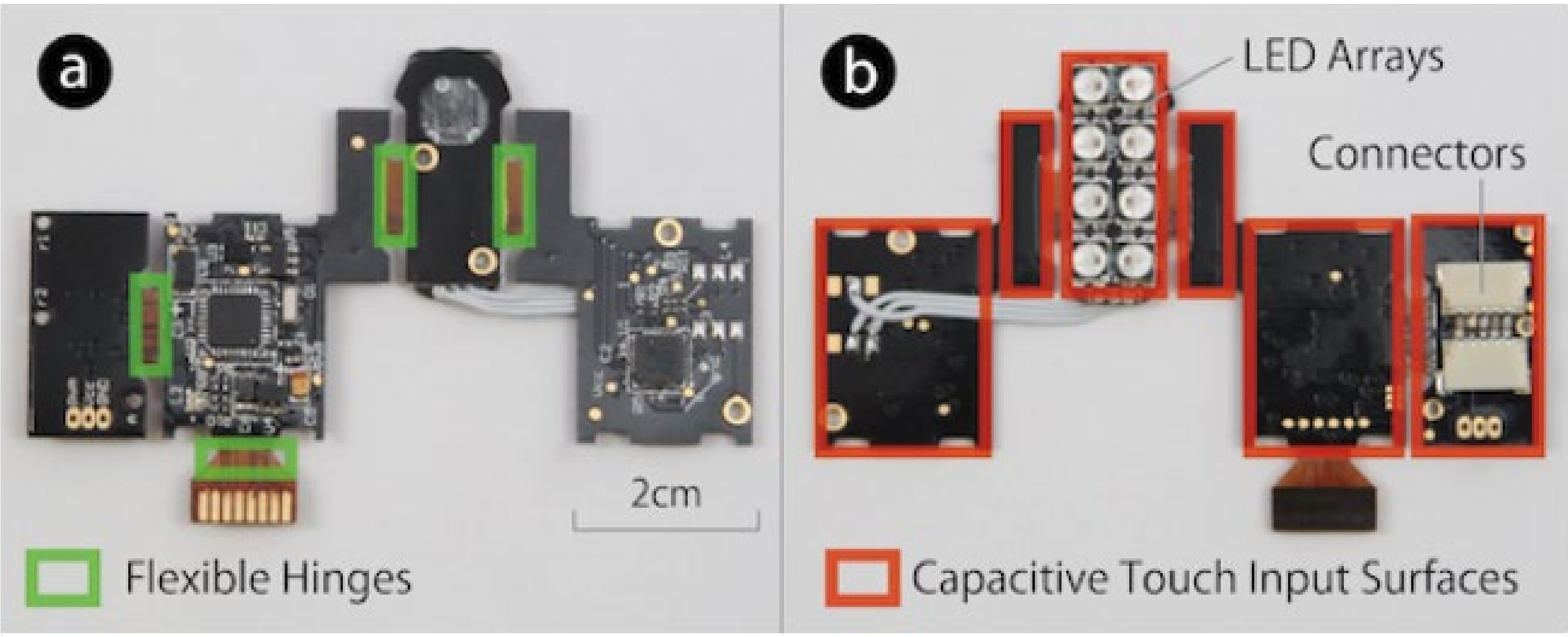


Figure 3. The components of each module (a: circuit board with flexible hinges, b: 3D printed bracket, c: HS-5035HD Servo Motor.



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[1]MIT Media Lab
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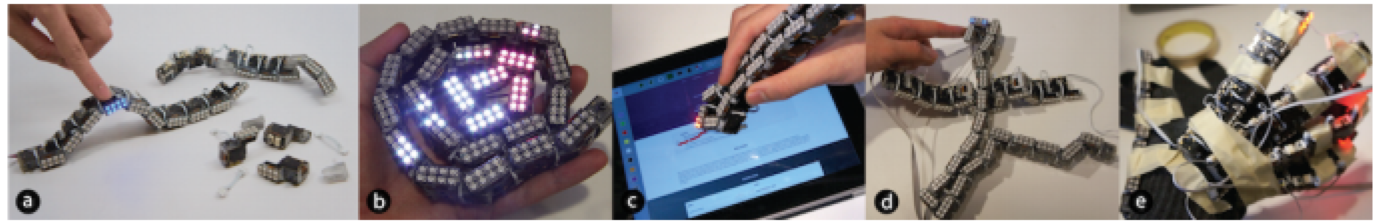
{ken_n, artemd, joep, ishii}@media.mit.edu

[2]Stanford University
Stanford, CA
sfollmer@stanford.edu



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Actuated Curve Interfaces; Shape Changing Interfaces; Modular Robotics

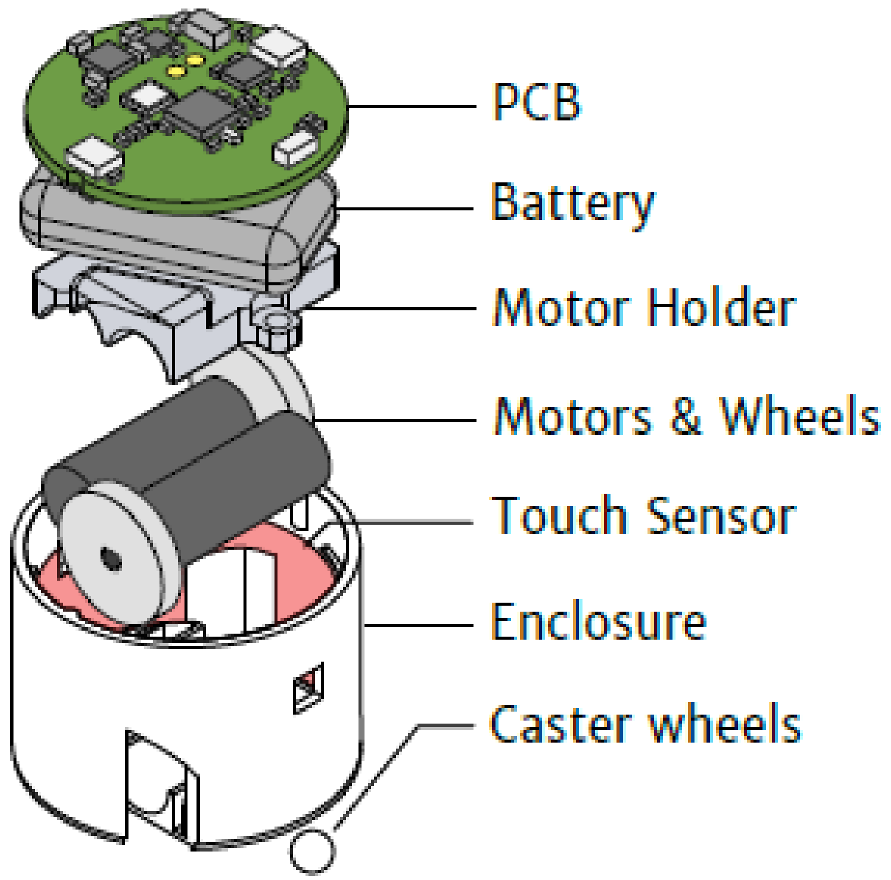
INTRODUCTION

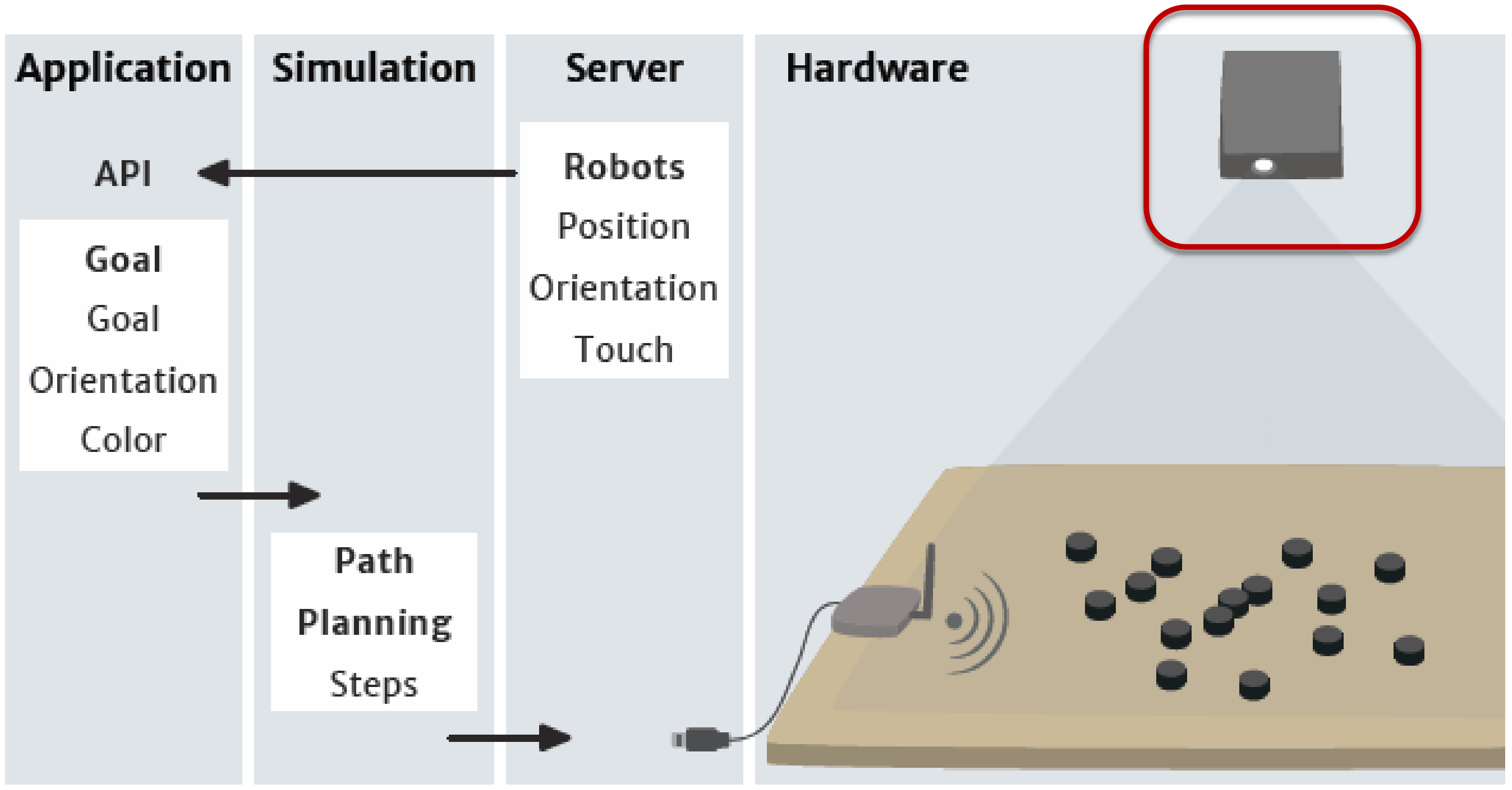
As shape changing interfaces being an emerging field in HCI, a lot of actuation techniques have been introduced to provide physical shapes to represent digital data and to embody spatial interactions [9, 4]. Researchers are continually seeking techniques that have a variety of transformational capabilities in different geometries and scales [14, 24]. To extend the sensing and display capability of such shape changing interfaces, extra sensors or cameras and projectors have been installed for detecting human input and displaying information on the active surfaces. However, this strategy poses a challenge for scaling the system, which presents a problem, especially for mobile applications. To push the boundaries of shape-changing interface research, another approach calls for self-contained systems that integrate sensing, actuation and display across different scales, geometries, and transformations.

We present ChainFORM: a modular integrated hardware system that has a chained, linear form factor (Figure 1). The hardware comprises identical actuated modules connected in series, which allows the user to customize the length and the configuration of devices they construct. The form-factor of line and the modularity expands the possibility of transformation for both shapes and scales. In addition, each module inte-

UIST 2016: Nakagaki et.al.

Robot Design





Zooids: Building Blocks for Swarm User Interfaces

Mathieu Le Goc[1,3,4], Lawrence H. Kim[2], Ali Parsaei[2], Jean-Daniel Fekete[1,4] Pierre Dragicevic[1,4], Sean Follmer[2]

[1]Inria, [2]Stanford University, [3]Université Paris-Sud, [4]Université Paris-Saclay

{mathieu.le-goc, pierre.dragicevic, jean-daniel.fekete}@inria.fr, {lawkim, aparsaei, sfollmer}@stanford.edu

Figure 1. *Zooids* can be held as tokens, manipulated collectively or individually, behave as physical pixels, act as handles and controllers, and can move dynamically under machine control. They are building blocks for a new class of user interface we call *swarm user interfaces*.

ABSTRACT

This paper introduces *swarm user interfaces*, a new class of human-computer interfaces comprised of many autonomous robots that handle both display and interaction. We describe the design of *Zooids*, an open-source open-hardware platform for developing tabletop swarm interfaces. The platform consists of a collection of custom-designed wheeled micro robots each 2.6 cm in diameter, a radio base-station, a high-speed DLP structured light projector for optical tracking, and a software framework for application development and control. We illustrate the potential of tabletop swarm user interfaces through a set of application scenarios developed with Zooids, and discuss general design considerations unique to swarm user interfaces.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

interact with *"a new kind of matter capable of changing form dynamically"* [26].

Several significant steps have been recently made towards Sutherland's and Ishii's visions, particularly through research on actuated tangibles [48, 50, 78] and shape displays [55, 56, 15]. However, current systems suffer from a number of limitations. First, actuated tabletop tangibles generally only support the manipulation and actuation of a few (e.g., 3–4) solid objects, which is not enough to emulate physical matter that can change form. On the other hand, shape displays try to achieve surfaces that can be deformed and actuated, but current implementations do not support arbitrary physical topologies. Furthermore, both types of systems traditionally use physical objects primarily as *input*, while *output* is almost always provided through separate pixel-based display technology. Although video-projected overlays allows input and output to spatially coincide [12], they provide only a limited sense of physicality [5]. Likewise, many such systems require heavy

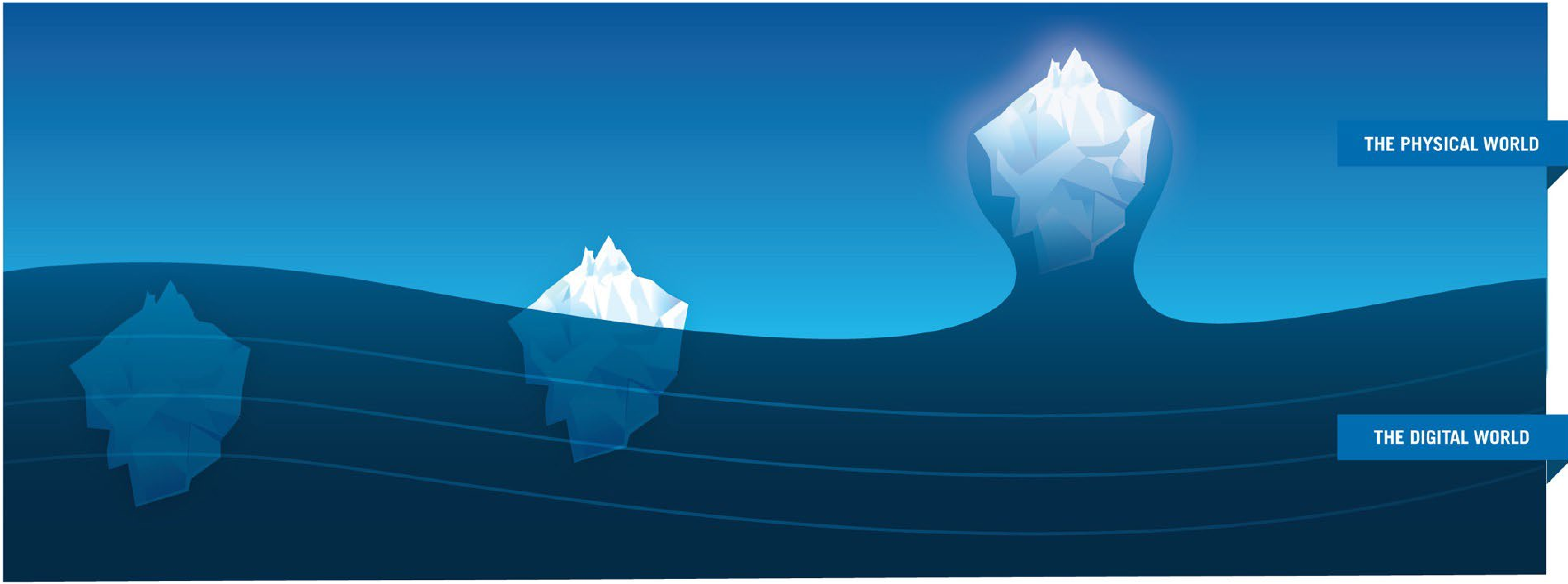
UIST 2016

Goc et al.

GUI PAINTED BITS

TUI TANGIBLE BITS

RADICAL ATOMS



Special thanks to Stefanie Mueller for the inspiring slides

2012: Hiroshi Ishii's vision: Radical Atoms

“Practical” Use?

Teaching Computer Science to 5-7 year-olds: An initial study with Scratch, Cubelets and unplugged computing

Benjamin Wohl
Highwire DCT
Lancaster University, Lancaster, UK
b.wohl@lancaster.ac.uk

Barry Porter Sarah Clinch
School of Computing & Communications
Lancaster University, Lancaster, UK
b.f.porter | s.clinch@lancaster.ac.uk

ABSTRACT

Changes to school curriculums increasingly require the introduction of computer science concepts to younger children. This practical report compares three existing tools for teaching computer science concepts: unplugged computing, tangible computing and MIT's Scratch. We specifically focus on the use of these tools for school pupils aged 5-7. We describe a comparative study with 28 pupils from three rural UK primary schools that explores engagement with, and effectiveness of, each tool. As far as we are aware this is the first such comparative study of its kind. We demonstrate that the studied tools can be used to successfully introduce core computer science concepts to pupils as young as 5 years of age, that the methods used by teachers to deliver computing curriculums may greatly impact the learning outcomes, and that particular care needs to be taken to ensure that pupils focus on learning concepts rather than learning tools.

Categories and Subject Descriptors

[**Social and professional topics**] Computing education – *Computer science education*

Keywords

Scratch; unplugged, Cubelets; computing curriculum; primary education; early years; tangible computing

1. INTRODUCTION

In recent years organizations such as Computing at School (CAS) have been advocating for more computer science to be taught in UK schools [3]. In September 2014, revisions to the English National Curriculum introduced computing as a statutory requirement for children at all stages of schooling. Although a positive development, many primary schools are faced with the new challenge of delivering computer science education to young pupils. The new UK Computing Curriculum begins with pupils aged 5–7. However, to date, little research has explored how to teach the complex concepts of computing to children of this age.

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In this paper, we explore techniques for teaching computing in school to some of the youngest pupils, with particular focus on delivery in small rural primary schools. We compare three different methods for teaching basic concepts of computer science to 5–7 year olds. Our research question is: *"What is the effectiveness of various methods of delivering the UK computing curriculum to key stage one pupils in small rural primary schools?"*

Motivated by the introduction of computing to the UK National Curriculum, the study was conducted in June 2014 (prior to implementation of the new curriculum in September 2014). We targeted three small schools in the North West of England. Within the study, pupils and schools were introduced to three different techniques for learning about computer science: unplugged computing, tangible computing, and Scratch programming. All three techniques have been used in prior work in the classroom or with children, with a range of age groups, but rarely has the focus been on assessing the effectiveness of delivering specific computer science concepts to very young children. As well as a lack of research in the area of teaching computing to this age group, there is particular need to compare various methods of classroom delivery of computational concepts, in order to support the future teaching of these topics [7].

2. RELATED WORK

In recent years a range of new resources have been developed to engage young people in computing. These include tools such as unplugged computing, tangible computing and screen-based environments such as Scratch. However, there is limited study of the effectiveness of these tools with younger pupils, and we are not aware of any research that performs comparisons across all three methods.

2.1 Computer Science Unplugged

Computer Science Unplugged (CS Unplugged) is an approach to teaching computer science where the pupils themselves enact the algorithms. The approach was initially developed at the University of Canterbury in New Zealand, with detailed descriptions of activities that use computational logic in an unplugged environment [4]. These activities range from creating algorithms to counting with binary. Use of CS Unplugged has mainly been studied with older children (high school and middle school) with a focus on pupil interest in the subject of computer science as separate from programming or ICT. However, the impact of this to date has mixed reports in the literature [1, 6].

shapeCAD: An Accessible 3D Modelling Workflow for the Blind and Visually-Impaired Via 2.5D Shape Displays

Alexa F. Siu[1], Son Kim[2], Joshua A. Miele[3], Sean Follmer[1]
[1]Stanford University [2]Vista Center for the Blind, [3]Smith-Kettlewell Eye Research Institute
[1]{afsiu, sfollmer}@stanford.edu, [2]skim@vistacenter.com, [3]joshua.a.miele@gmail.com

Figure 1. We investigate an accessible 3D modelling workflow (shapeCAD) where 3D models are generated through OpenSCAD, a declarative programming language for 3D modeling, and rendered at interactive speeds in a 2.5D shape display consisting of a grid of 12×24 actuated pins.

ABSTRACT

Affordable rapid 3D printing technologies have become key enablers of the Maker Movement by giving individuals the ability to create physical finished products. However, existing computer-aided design (CAD) tools that allow authoring and editing of 3D models are mostly visually reliant and limit access to people with blindness and visual impairment (BVI). Through a series of co-design sessions with three blind users of mixed programming ability, we identify accessibility challenges in existing 3D modelling scripting tools and design interactions to support dynamic feedback of scripts using a 2.5D tactile shape display. With these insights, we implement shapeCAD. Interacting with shapeCAD, BVI users are able to leverage the low resolution output from a 2.5D shape display to complement programming of 3D models. shapeCAD allows users to haptically explore and modify existing models, and to author new models. We further validate usability and user experience through an evaluation with five BVI programmers. In a short period of time, novices were able to design a range of new objects. BVI users can bring a valuable perspective to design and it is imperative to increase accessibility in tools that enable this community to also participate as designers.

ACM Classification Keywords

Human-centered computing Accessibility systems and tools

Author Keywords

Accessible Authoring Tools; Accessible 3D Printing; Tactile Graphics; Haptics; Tactile Displays; 2.5D Shape Displays

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http://dx.doi.org/10.1145/3308561.3353782

INTRODUCTION

People with blindness and visual impairments (BVI) are experienced *makers* having to be adept at using the technology at hand to solve accessibility problems they face in their daily lives. This spirit of creative problem solving and tinkering in the BVI community has mostly existed in parallel to the mainstream *Maker Movement* because most *maker* tools are inaccessible. The rise in less expensive and distributed fabrication tools, such as 3D printers and easy-to-use micro-controllers, have made it easier for a wide range of groups to engage in *making* [19]. Yet accessibility remains a challenge and the BVI community, which may benefit immensely from such tools, remains marginalized [22, 53]. Accessibility in *making* can not only provide access points for contextualized learning of many concepts considered critical for STEM but can also give BVI people the tools to participate in the vibrant maker culture as designers themselves [3, 8, 19, 53] and act independently to make the things they want and need. In this paper we focus on identifying and addressing accessibility challenges in the areas of 3D modelling and 3D printing for the BVI.

Current commercial and open source Computer-Aided Design (CAD) tools that support viewing, authoring, and editing of 3D models are mostly visually reliant and limit access for BVI people. This is a limitation not only in terms of the lack of feedback as models are created but also in terms of the user interface, as most modern programs rely on direct manipulation with graphical user interfaces which are not easily accessible. Programming-based tools for 3D modelling, such as OpenSCAD [40], address some issues of access for defining 3D models, yet feedback on the geometry of the model is not available [35]. 3D printing the model can serve as feedback itself, however, the time between iterations can take several hours; this discourages its use and methods to interactively visualize the resulting 3D model do not exist [24].

TangibleGrid: Tangible Web Layout Design for Blind Users

Jiasheng Li
jsli@umd.edu
University of Maryland
College Park, Maryland, USA

Zeyu Yan
zeyuy@umd.edu
University of Maryland
College Park, Maryland, USA

Ebrima Jarjue
ebjarjue@terpmail.umd.edu
University of Maryland
College Park, Maryland, USA

Ashrith Shetty
ashrith@terpmail.umd.edu
University of Maryland
College Park, Maryland, USA

Huaishu Peng
huaishu@cs.umd.edu
University of Maryland
College Park, Maryland, USA

ABSTRACT

We present TangibleGrid, a novel device that allows blind users to understand and design the layout of a web page with real-time tangible feedback. We conducted semi-structured interviews and a series of co-design sessions with blind users to elicit insights that guided the design of TangibleGrid. Our final prototype contains shape-changing brackets representing the web elements and a baseboard representing the web page canvas. Blind users can design a web page layout through creating and editing web elements by snapping or adjusting tangible brackets on top of the baseboard. The baseboard senses the brackets' type, size, and location, verbalizes the information, and renders the web page on the client browser. Through a formative user study, we found that blind users could understand a web page layout through TangibleGrid. They were also able to design a new web layout from scratch without the help of sighted people.

CCS CONCEPTS

• **Human-centered computing → Accessibility systems and tools**.

KEYWORDS

Accessible web design, tactile feedback, tangible user interface, visual impairment, accessibility

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1 INTRODUCTION

Assistive technologies have greatly changed the lives of blind and visually impaired people. Beyond Internet consumers, blind users are now able to share stories and life events on social media sites such as YouTube [21] and Instagram [38]; some blind users have also created and maintained their own web pages for blogging and knowledge sharing [18, 33]. Indeed, the stories and daily experiences of the blind media influencers have become an important source of support to the blind community. Mastering skills like building web pages has also led to new employment opportunities for blind and visually impaired people [9, 10].

Unfortunately, creating a web page is still challenging for many blind users despite the strong need for it [33, 37]. For one, web

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Figure 1: TangibleGrid overview. a) The complete system of Tangible grid; b) a participant is exploring a web page layout; c) designing a new layout by resizing and placing a bracket to the baseboard.

Optional readings

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 in museums such as the Collection of Historic Scientific Instruments at Harvard University (Fig. 1).

We were inspired by the aesthetics and rich affordances of these historical scientific instruments, most of which have disappeared from schools, laboratories, and design studios and have been replaced with the most general of appliances: personal computers. Through grasping and manipulating these instruments, users of the past must have developed rich languages and cultures which valued haptic interaction with real physical objects. Alas, much of this richness has been lost to the rapid flood of digital technologies.

We began our investigation of "looking to the future of HCI" at this museum by looking for what we have lost with the advent of personal computers. Our intention was to rejoin the richness of the physical world in HCI.

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 aware of a change in weather through ambient light), most of these practices are neglected in current HCI design because of the lack of diversity of input/output media, and too much bias towards graphical output at the expense of input from the real world [3].

Outline of This Paper

To look towards the future of HCI, this paper will present our vision of Tangible Bits and introduce design projects including the metaDESK, transBOARD and ambientROOM systems to illustrate our key concepts. This paper is not intended to propose a solution to any one single problem. Rather, we will propose a new view of interface and raise a set of new research questions to go beyond GUI.

FROM DESKTOP TO PHYSICAL ENVIRONMENT

In 1981, the Xerox Star workstation set the stage for the first generation of GUI [16], establishing a "desktop metaphor" which simulates a desktop on a bit-mapped

CHI 1997

Ishii et.al. from MIT

Itsy-Bits: Fabrication and Recognition of 3D-Printed Tangibles with Small Footprints on Capacitive Touchscreens

Martin Schmitz
schmitz@tk.tu-darmstadt.de
TU Darmstadt
Darmstadt, Germany

Florian Müller
mueller@tk.tu-darmstadt.de
TU Darmstadt
Darmstadt, Germany

Max Mühlhäuser
max@tk.tu-darmstadt.de
TU Darmstadt
Darmstadt, Germany

Jan Riemann
riemann@tk.tu-darmstadt.de
TU Darmstadt
Darmstadt, Germany

Huy Viet Le
mail@huyle.de
University of Stuttgart
Stuttgart, Germany

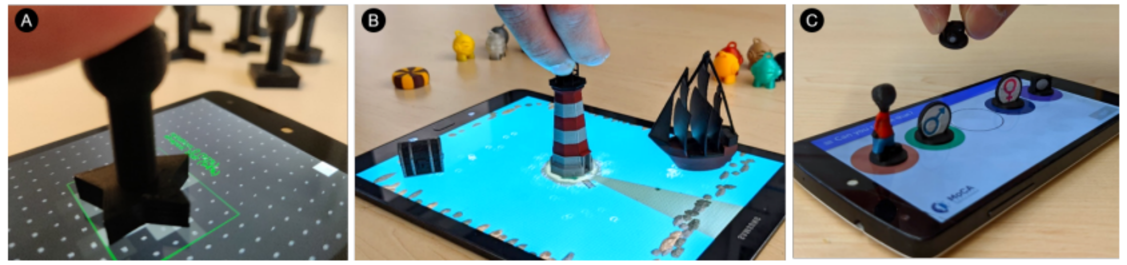

Figure 1: Itsy-Bits recognizes 3D-printed tangibles as small as a fingertip via the capacitive image of an embedded conductive shape (A). This opens up a variety of tangible user interfaces on the most common form factors of touchscreens, such as individualized interactive board games (B) or a more tangible learning experience (C).

ABSTRACT

Tangibles on capacitive touchscreens are a promising approach to overcome the limited expressiveness of touch input. While research has suggested many approaches to detect tangibles, the corresponding tangibles are either costly or have a considerable minimal size. This makes them bulky and unattractive for many applications. At the same time, they obscure valuable display space for interaction.

To address these shortcomings, we contribute Itsy-Bits: a fabrication pipeline for 3D printing and recognition of tangibles on capacitive touchscreens with a footprint as small as a fingertip. Each Itsy-Bit consists of an enclosing 3D object and a unique conductive 2D shape on its bottom. Using only raw data of commodity capacitive touchscreens, Itsy-Bits reliably identifies and locates a variety of shapes in different sizes and estimates their orientation. Through example applications and a technical evaluation, we demonstrate the feasibility and applicability of Itsy-Bits for tangibles with small footprints.

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CCS CONCEPTS

• **Human-centered computing → Interaction devices.**

KEYWORDS

Touchscreen; 3D Printing; Tangibles; Machine Learning

ACM Reference Format:

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1 INTRODUCTION

Today, touch-enabled devices are ubiquitous, ranging from smartphones and tablets to wall-sized displays. While the concept of touch is easy to understand, it is often criticized as lacking input expressiveness as it only encodes a single point of touch [53]. As one solution, research has proposed interactive tangible objects (in short, *tangibles*) that, when placed on a touchscreen, enable haptic control of on-screen contents by identifying the object together with its location and orientation [8, 26, 45, 59]. This strand of research has also proposed a great variety of interaction techniques that can be performed with tangibles, ranging from touch [51, 63] and deformation [3, 53, 60] to physical controls [19, 28, 62] and construction [5, 8, 33]. Remarkably, despite this large body of research,

CHI 2021

Schmitz et.al.

Material is in part based on the lectures by Prof. Stefanie Mueller @ MIT and Prof. Kimiko Ryokai @UCB