Tangible and Embodied Interaction

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Abstract

Tangible and Embodied Interaction, or TEI, is a growing area of human-computer interaction (HCI) research that aims to expand opportunities for digital interaction through physical world objects, surfaces, and spaces, by incorporating diverse sensing technologies and materials. As an approach to HCI design, TEI emphasizes the use of human motor skills and real-world social practices in the creation of digital technologies and experiences that unfold in physical spaces, away from the confines of the traditional desktop computer. From early examples of Tangible User Interfaces to an expanding focus on Embodied Interaction, the field has evolved and matured since its beginnings in the late 1990s. This chapter aims to provide an introduction to the field of TEI for students, researchers, and practitioners alike. It begins with an overview of the history, theoretical foundations, and emerging frameworks for the field, and then dives into a review of TEI interactions and their underlying technical implementations. This is followed by a survey of application areas that have been addressed by the TEI community and a discussion of how these can provide value in people's lives.

1. Introducing Tangible and Embodied Interaction

This chapter will provide a brief overview of the field of Tangible and Embodied Interaction (TEI). For a deeper dive into this area, please see the following books: *Tangible User Interfaces: Past, Present, and Future Directions* (Shaer & Hornecker, 2010) and *Weaving Fire Into Form: Aspirations for Tangible and Embodied Interaction* (Ullmer et al., 2022).

TEI covers Human-Computer Interaction (HCI) research that has a physical component, such as a physical device or set of physical objects that, through embedded electronics or other sensing approaches, will respond to a person's physical actions. It is important to note that there is both conceptual and practical overlap with other areas of HCI research, including Wearable Interaction, Mixed Reality, Ubiquitous Computing, and Interactive Surfaces and Spaces, which all share the vision of providing ways to move technologies off the computer screen and into our physical environment.

As an example of TEI, take Cueb (Golsteijn & van den Hoven, 2013), a cube that has six displays (one on each side) for showing someone's digital photographs (see Figure 1). By shaking the cube, it shows six new photos. There is more to the cubes, as they are designed to enhance communication between parents and teenagers, but TEI does not limit itself to an application area, it is the interactive objects themselves that represent TEI well. The cubes have a physical form, allow for different types of physical manipulation (of which shaking is one), and the cubes respond to a person's actions through embedded electronics, connecting the physical with the digital and encouraging the human body, senses, and skills to be used while interacting with technology. The latter is something that gets lost more and more in today's increasingly digitized world, focusing on visual displays with either keyboard or speech input.

Figure 1: *The Cueb system consists of two cubes that each contain six displays for showing a person's digital photos (Golsteijn & van den Hoven, 2013). Photo: Connie Golsteijn. [ALT TEXT: The photo shows the Cueb system, with two Cueb devices sitting on a tabletop. Each Cueb device has six displays, one on each side, that are used to show a person's digital photos.]*

The field, theories, and definitions of tangible and embodied interaction have evolved over time, as can be seen in **Section 2: Presenting History and Theory**. In **Section 3: Designing and Implementing Interactions** we dive deeper into the interactions that form the foundation of

TEI, as well as the technologies and approaches that make these interactions possible. **Section 4: Exploring and Experiencing Applications** gives examples of application areas that are popular in the TEI community to show the breadth of work done in TEI and to indicate opportunities for providing value in people's everyday lives. Finally, the chapter wraps up with some final thoughts and directions for future work in **Section 5: Conclusions**.

2. Presenting History and Theory

In many ways, tangible and digital media seem at odds with one another; the former constrained by the laws of physics and the (relatively) fixed nature of materials, and the latter liberated by the seemingly infinite malleability and scalability of computational representations. Yet the development of artifacts, information, and knowledge have been intertwined throughout history, connecting the concrete with the abstract, the tangible with the conceptual. In a 1997 CHI conference paper, Hiroshi Ishii and Brygg Ullmer laid out a vision for what they called "Tangible Bits" (Ishii & Ullmer, 1997) – the idea that digital information can be coupled to everyday physical objects and surfaces that either live at the center (as tangible interfaces), or at the periphery (as ambient displays), of human attention. Their work built on related efforts, most immediately the graspable user interfaces proposed by Fitzmaurice et al. (1995), as well as a variety of digitally connected physical artifacts before that. It represented an important step in the HCI field's attempts at foregrounding physical bodies, skills, and experiences in the design of interactive digital technologies. Ishii and Ullmer began their work with a visit to the Harvard University Collection of Historic Scientific Instruments, where they explored the richness of physical artifacts that served as tools to capture information and represent complex ideas, and whose creators had long since placed immense value on craftsmanship and manual skills. This section presents a brief overview of the historic origins of TEI, from artifacts that pre-date digital technologies but serve as inspiration for TEI in the way they embody knowledge in material ways, to foundational concepts, theoretical frameworks, and early examples that helped to open a direction for this growing area of research.

2.1 Looking Back

The Tangible Bits paper (Ishii & Ullmer, 1997) told the story of two-year-old Hiroshi Ishii's first encounter with a physical counting device called an abacus. This story illustrated the idea of a tangible interface and served to suggest a path forward for the field of HCI. Typically made of wood, an abacus consists of a frame that is fitted with vertical rods on which beads slide up and down. The beads represent numbers, and by sliding them up and down with the fingers, a person can perform the mathematical operations of addition, subtraction, multiplication, and division. As such, the abacus is an artifact that connects the tangible with the intangible, linking abstract mathematical concepts to its graspable components.

Many other artifacts throughout history have done the same. An early example were the clay tokens from the Near East, dating from as far back as 9,000 BC, that were used to keep track of reserves of cultivated goods. These tokens have been described as the "fountainhead" of abstract systems of writing and counting by Schmandt-Besserat (1992). Her research has suggested that the need to count arose with the cultivation of cereals and with an economy based on the redistribution of goods (Schmandt-Besserat, 2019). Counting in turn led to writing, and numeracy and literacy thus arose in tandem, the former linking physical tokens of different shapes (cones, spheres, disks, etc.) to different meanings that aided in physically and cognitively managing the growing agrarian economy of the time. In other words, like the abacus, these tokens were early tangible interfaces, albeit with no digital world to link to, only a conceptual and cognitive one.

Over time, the tangible interfaces to the cognitive and conceptual world became increasingly complex, highlighting the ongoing evolution of human societies and a growing body of scientific and cultural knowledge across the world. The Orrery from the 18th century, a mechanical device that both calculates and represents the movement of planets around the sun, as well as the physical double helix model of DNA built by Watson and Crick in 1953, are examples of how artifacts can embody knowledge and serve as tools for both thinking and communicating about natural phenomena (Baird, 2004). We can also look across cultures, to examples like the Quipu of the Inca, which were textile cords on which knots were placed as a means of record keeping (Ascher & Ascher, 1981), or the beautifully crafted Lukasa boards of the Luba peoples of central Africa (see Figure 2), which connected elements of a tribe's history and genealogy to the physical components of the board, such as beads and carvings (Roberts & Roberts, 1996).

Figure 2: *An authentic African Lukasa board that was loaned by the Royal Museum for Central Africa for the Mapping Place exhibition at the Robert C. Williams Museum of Papermaking. Photo: Sidarth Kantamneni. [ALT TEXT: The photo shows an authentic African Lukasa board against a black background. The Lukasa is a wooden board that is decorated with beads and carvings.]*

2.2 Foundational Concepts

Beyond intentionally crafted associations between the tangible and the conceptual, and as Hiroshi Ishii discovered when he was a child, the physical form of an artifact can often afford certain other uses in practice, like the abacus that becomes a toy train or musical instrument for a small child (Ishii & Ullmer, 1997). The concept of "**affordance**" was first introduced by James

Gibson (1979) to describe the actions that an environment or object makes possible. Don Norman later adopted the term in the context of product design with the idea of (perceivable) affordances as indications as to how a designed artifact is to be used (Norman, 1988), and later the idea of (social) "**signifiers**" as cues that help to interpret the current state of the environment and that may point to appropriate social behavior (Norman, 2008).

Norman (1991) also introduced the term "**cognitive artifacts**" to describe artifacts that aid our cognition because they act as representations through which we can manipulate information, allowing us to work with (and think about) it in new and different ways. He distinguished between surface representations that are visible to humans, and internal representations that require an interface to be interpreted by humans. He pointed out that a significant concern for interface design is the relationship or mapping that is established between the control of information and the display of the system state. A key aspect of the abacus described above is that the sliding beads both *control* the mathematical operations and *represent* their current state. This is a common feature of mechanical systems. Imagine, for example, a lever valve that enables or blocks the flow of water down a pipe. In contrast, computer systems have tended to separate control and representation. We press, for example, a key labeled "return" or "enter" on our keyboard, and the on-screen cursor in our text document moves to the next line.

The idea of "**direct manipulation**" (Shneiderman, 1983) offered a partial solution to the problem of separated control and representation, as it relies on providing an appropriate representation of virtual objects and allowing users to act on them directly with immediate feedback. Nevertheless, in traditional graphical user interfaces (GUIs) on desktop computers, the physical artifact used for control (mouse, keyboard) has inevitably remained separate from the artifact that represents the system state (computer screen). This is highlighted in the Model-View-Controller (MVC) interaction model for GUI systems (Krasner & Pope, 1988). In contrast, Ullmer and Ishii (2001) centralized the idea of a close coupling between control and representation in the interaction model they defined for tangible interfaces, called MCRit (Model-Control-Representation intangible and tangible). They also suggested different ways in which this close coupling can be realized in practice according to spatial, constructive, and relational approaches (Ullmer & Ishii, 2000).

Another key concept for the area of TEI is that of "**embodiment**". In his book *Where the Action Is* (2001), Paul Dourish built on ideas of tangible and social computing, as well as the ideas of a branch of philosophy called phenomenology, to define the foundations for what he called "**embodied interaction**." Central to this is the notion that we exist and act in the real world around us. It is in this situated context, in our interaction with artifacts and with each other, that we create, manipulate and share meaning. Hornecker and Buur (2006) later expanded the Ullmer and Ishii (2001) definition of tangible user interfaces by providing a framework for "**tangible interaction**" that connects physical representation and tangible manipulation with embodied interaction and embeddedness in real space. Tangible interaction and embodied interaction thus complement one another, with the former highlighting the physicality, representational power, and action potential of physical artifacts, surfaces, and spaces, and the latter emphasizing the role of our bodies in engagement with the physical and social world.

Tangible interaction has thus tended to reference works that involve physical artifacts as part of the interactive experience (such as tangibles tracked on an interactive surface), while embodied interaction has more often referenced those in which bodies move in space (such as systems that track full-body interaction). It is important to note that as these terms have been adopted in practice, they are often not mutually exclusive, and many systems reference TEI as a unified idea.

2.3 Early Examples of TEI

Although tangible and embodied interaction was formalized in the late 1990s through early 2000s and has matured and grown considerably since then, there are numerous earlier examples that have served as inspirations for the research community. The tangible interface instances covered in Ullmer and Ishii (2000) provide a nice overview of the field's origins. We look at some of the key examples here but also broaden our frame to consider more embodied approaches as well. The examples cover the areas of architecture, art and design, education, communication, and personal and scientific productivity.

Architecture: Physical modeling has been a part of architectural practice for centuries, helping to test out and think through different options by visualizing the imagined design in three dimensions. It will thus hardly come as a surprise that some of the earliest examples of tangible interfaces can be traced to the field of architectural design. By the 1960s, the emerging area computer-aided architectural design (CAAD) was demonstrating the power of computers in automating the design process with mathematical/geometric models (Sdegno, 2016), for example by generating different cross-section views or evaluating design solutions based on different performance measures. However, as noted by Aish and Noakes (1984), the (text and 2D graphical) interfaces of the time were a barrier to the adoption of early CAAD systems. Their work in the late 1970s involved the design of the Building Block System (BBS) (Aish, 1979; Aish & Noakes, 1984), which consisted of modular blocks with physical and electrical contacts that represent building components, and a baseboard on which these blocks could be assembled to create a "tangible model" (Aish & Noakes, 1984) of the design. The spatial configuration of the blocks could be detected by the CAD system on the host computer, which could display the model on-screen, generate alternate views, and evaluate the building's performance. Similarly motivated by the idea that a keyboard and mouse were poorly suited for manipulating models, John Frazer and colleagues independently began to experiment with Machine-Readable Models in the late 1970s (Frazer et al., 1980, 1981). These also consisted of modular physical blocks, in this case cube-shaped, that could be physically/electronically connected and read by a grid-board system. The cubes contained LEDs that visualized the search path as the spatial geometry was mapped by the system. The early prototypes of Machine-Readable Models eventually led to the Universal Constructor system (Frazer, 1995), a large-scale model that was used for different experimental design applications such as evolutionary architectures.

Interactive art: Aish, Frazer, and their colleagues were not the only researchers who found themselves dissatisfied with the way human-computer interactions were taking shape in the 1960s and 70s. Myron Krueger, whose work centered on the idea of "responsive environments," wrote: “Man-machine interaction is usually limited to a seated man poking at a machine with his fingers or perhaps waving a wand over a data tablet” (Krueger, 1977). In contrast, his responsive environments, which unfolded as a series of interactive art pieces realized over more than a decade, involved computer systems that would sense a human’s actions within a given space, and would respond intelligently through audiovisual media. These pieces, which included works such as METAPLAY and VIDEOPLACE (Krueger, 1977), demonstrated a kind of artistic embodied interaction that centralized the relationship between action and response over their visual and auditory aesthetic.

Education: Around the same time as the early architectural examples of tangible interfaces, the TORTIS system (1976) developed by Radia Perlman demonstrated how physical interfaces can teach children to program a small computer-controlled robot called a “turtle”. This turtle could move forward/backward and rotate, and was equipped with a pen, light, and horn. Perlman designed two interfaces for programming the turtle’s behavior. The first one (the Button Box) consisted of buttons representing different commands grouped into boxes. The second (the Slot Machine) consisted of plastic cards representing actions, numbers, or conditionals, which could be placed into slots that were arranged in rows. Perlman’s motivation for building these physical programming interfaces was the observation that learning to communicate with computers could be a valuable experience for children, but that the conventional keyboard interface was discouraging for them. TORTIS offered an “imaginative computer environment” that supported a fun, exploratory approach toward learning abstract concepts, such as numeracy, geometry, and procedural thinking. This early foray into the use of tangibles in an educational context has been picked up by many researchers since then, as discussed further in Section 4.1.

Graphic design: In the early 1990s, Fitzmaurice, et al. (1995) criticized the dominant keyboard/mouse interaction paradigm when they proposed the concept of graspable user interfaces, which they demonstrated in the context of a graphical design application that used two-handed interactions with physical bricks on a drafting-table surface called the ActiveDesk. They argued that input devices could be regarded as being *time-multiplexed* or *space-multiplexed*, where the former limits the user to sequential actions (like a mouse), while the latter involves multiple control points that each occupy their own space, allowing parallel interactions and more specialized context-sensitive input, and leveraging human spatial reasoning and manual skills.

Communication: The idea of space-multiplexing can also be seen in the context of the Hydra videoconferencing system (Buxton et al., 1997; Sellen et al., 1992), where each remote participant is embodied by a separate unit consisting of a video monitor, camera, and loudspeaker. The user can spatially arrange these units in their own space to mimic the arrangement of physical participants around a conference table. This means that the view and voice of each conference participant will emanate from a distinct spatial location, thereby preserving some of the actions that are essential components of human conversation, such as head turning and gaze direction. Another classic example in the domain of communication is the Marble Answering Machine (Crampton-Smith, 1995). Conceived by Durrell Bishop when he was a student at the Royal College of Art, the Marble Answering Machine embodied voicemail messages as marbles that rolled out of a chute on an answering machine as they were received. The user could physically pick up a marble, drop it into a small indentation on the answering machine to listen to it, and then drop it back into the marble chute to delete the message. Like the beads on an abacus, each marble and its position on the answering machine served as both control and representation for the voicemail system. The piece has been widely described as a classic example of and inspiration for tangible interaction design.

***Personal and scientific productivity*:** Computer interfaces have greatly enhanced the way humans record, organize, and make sense of information. As far back as the 1940s, Vannevar Bush (1945) described his vision of the "memex", a desk-shaped information retrieval device at which a person could create associative trails through a database of documents and records. The memex is often referenced as a precursor to hypertext, and it was an important inspiration for future HCI and digital media pioneers like Douglas Engelbart and Ted Nelson (Wardrip-Fruin & Montfort, 2003). Equally interesting from a TEI perspective, however, is Bush's envisioned design of the memex as a physical desk, with levers that can be moved forward/backward for navigation, and a stylus for taking notes. Beyond the memex, Bush's article also described wearable information devices that would allow a future scientist to move through the field or laboratory, making records (via camera) and notes (via speech) with hands free, without being anchored. These ideas highlight a vision for the future in which interacting with information integrates seamlessly into physical-world activities. Nearly 50 years later, Pierre Wellner's work on the DigitalDesk (1993) explored similar ideas of information retrieval and notetaking on a physical desk, but with a new spin given the advances in digital technologies in the intervening decades: users could work with both digital documents projected onto the desk as well as with paper ones, moving information between these two modalities using both pen and touch interaction. In a different context but similarly focusing on natural interactions to increase productivity, Hinckley et al. (1994) explored the use of physical props with embedded position and orientation trackers, such as a doll's head and a cutting plane, to navigate brain imaging data in a neurosurgical planning task. Some of the core ideas in Hinckley et al.'s work has become central to TEI design, including two-handed interaction, tactile and kinesthetic feedback, and direct action-task correspondence, all of which allowed the surgeons to leverage existing physical skills in their interactions with digital data.

2.4 Theories and Frameworks

As TEI has grown and matured as a field, researchers and designers have delved into the underlying philosophical and cognitive theories that inform TEI design and have offered frameworks to help organize and understand the design space. Although a comprehensive overview is beyond the scope of this chapter, we provide a brief overview of the key perspectives here. For a more in-depth overview, we encourage readers to look at chapters 3 and 4 of *Weaving Fire into Form: Aspirations for Tangible and Embodied Interaction* (Ullmer et al., 2022). It is also worth noting that a detailed review of TEI frameworks is provided by Mazalek and van den Hoven (2009). Their map of the TEI framework space across different facets (technologies, interactions, physicality, domains, and experiences) and types (abstracting, designing, and building) is intended to guide designers in choosing an appropriate framework for their specific goals.

In Section 2.2, we described some of the foundational concepts that informed and inspired TEI research and design. The concept of embodiment, in particular, is central to a broad perspective shift that has taken place in the HCI community over the past several decades. This has been described by Harrison et al. (2007), who noted that HCI approaches were initially rooted in human factors (termed the “first paradigm”), then in cognitivism (the “second paradigm”), and most recently in embodiment (the “third paradigm”). In the first paradigm, the focus of HCI was on ergonomics and engineering design, with the aim of optimizing the man-machine coupling. In the second paradigm, human minds and computers were viewed as separate information processors that need to communicate with each other. On the human side, information was understood to be taken in through our perceptual system, then processed in our brains, which resulted in an action via our motor system. On the computer side, HCI design according to this paradigm followed the MVC model mentioned above (Krasner & Pope, 1988), which similarly separates the model (brain) from the view (perception) and the control (action). From a philosophical perspective, this second paradigm was rooted in the theory of mind/body dualism formulated by Rene Descartes in the 17th century. In contrast, the third paradigm is rooted in the ideas of 20th century phenomenologists such as Martin Heidegger (1927), Maurice Merleau-Ponty (1945), and Alfred Schutz (1932). Phenomenologists rejected mind/body dualism in favor of a view of human consciousness as grounded in bodily experiences within the physical and social world. Most recently but still within the vein of the third paradigm, the areas of postphenomenology (Ihde, 2009), as well as somatics (Hanna, 1995) and somaesthetics (Shusterman, 1999, 2008), have also started to influence TEI research and design. Postphenomenology expands phenomenological ideas by putting technology and its social and cultural roles as the centerpiece. Postphenomenologists seek to analyze and understand technologies in practice, looking at the diverse ways that they mediate and shape the connection between humans and the world. Somatics is a philosophical perspective and area of bodywork that emphasizes body awareness through subjective, first-person perception, while somaesthetics seeks to understand how attending to our senses and bodily performance can improve our lived experience.

The philosophical ideas that have influenced the third paradigm of HCI also have their parallel in the cognitive sciences within an area of research that is broadly captured under the term “embodied cognition”. While embodied cognition includes a variety of theoretical perspectives and debates (Shapiro, 2011; Wilson, 2002), the overarching idea is that our perceptual, motor, and cognitive systems are tightly connected, and therefore our bodily experiences, social interactions, and environment all play an important role in the way we solve problems and understand the world. Specific perspectives that have influenced TEI include the theory of distributed cognition (Hutchins, 1995), the role of metaphors in cognition (Lakoff & Johnson, 1980, 1999), the idea of epistemic vs. pragmatic actions (Kirsh & Maglio, 1994), and the enactive view of cognition as an ongoing coupling to the environment through sensorimotor activity (Varela et al., 1991).

The ideas from phenomenology and embodied cognition have served as the foundation for numerous frameworks that have been used to describe, analyze, and design for TEI. These include the tangible interaction framework by Hornecker and Buur (2006) mentioned above, as well as the five themes for interaction design articulated by Klemmer et al. (2006): thinking through doing, performance, visibility, risk, and thickness of practice. A unifying framework called Reality-Based Interaction (RBI) was proposed by Jacob et al. (2008) to capture a range of "third paradigm" interaction styles, including TEI, augmented and virtual reality (AR/VR), and ubiquitous and pervasive computing. The RBI framework is organized around four themes: naïve physics, body awareness and skills, environment awareness and skills, and social awareness and skills. Around the same time, Fernaeus et al. (2008) described a conceptual shift from what they termed the "information-centric" view of tangible interaction proposed by Ullmer and Ishii (2000, 2001) that focused on mappings between digital information and tangible representations, to an "action-centric" view in which tangibles serve as resources for action in different ways based on their physical form and material properties as well as their personal and social relevance. Hurtienne and Israel (2007) directly extended prior work from philosophy and linguistics on metaphorical mappings between image schemas and abstract concepts, such as the schema of "up-down" mapping onto "good-bad" (Lakoff & Johnson, 1980, 1999), to propose a framework for the design of tangible interfaces based on schemas of space, containment, force, and attribute. Notably, the first two categories, which involve spatial relationships between tangibles and tangibles as containers, have been considered in other TEI frameworks as well, including Holmquist et al.'s (1999) work on token-based access to digital information and the Token and Constraint (TAC) paradigm by Shaer et al. (2004), among others. Drawing on three different flavors of embodied cognition, van Dijk et al. (2014) called for a move beyond distributed cognition to consider TEI design from the perspectives of "socially situated practice" and "sensorimotor coupling and enactment". For the former they suggest designers consider how computer systems fit into the existing physical world and social practices of users, rather than how to design interfaces for users to access the digital world. For the latter they ask designers to view interaction not as information access through embodied interaction, but rather as a feedback loop where meaning is created through sensorimotor coupling. More recently, researchers such as Höök (2018) and Loke and Schiphorst (2018), have proposed a somaesthetic approach for HCI design, which incorporates body, movement, perception, self-observation, and first-person methodologies into the design of emerging technologies, including different kinds of TEI experiences.

While many frameworks address questions of TEI design, there has also been some work on frameworks for evaluating user interactions with tangible systems. The idea of epistemic vs. pragmatic actions from Kirsh and Maglio's (1994) studies of Tetris players have been especially useful in this respect. Pragmatic actions are defined as those which brings users closer to their goal, while epistemic actions change the world in a way that supports the cognitive process. This distinction has been used to compare how users solve puzzles in tangible vs. multi-touch conditions (Antle & Wang, 2013). Building on this, Esteves et al. (2015) proposed the Artifact, Tool, Body (ATB) video-coding framework, a useful tool for analyzing the actions that users make with tangible systems and how well they support spatial problem-solving tasks. Likewise for the purpose of analyzing user experiences with TEI, Jensen and Aagaard (2018) have described how postphenomenological concepts, such as the idea of “multistability” (Rosenberger, 2014) (i.e., the different possible purposes an artifact or technology can take in different contexts), can be used to analyze the way people experience tangible and embodied interfaces such as a shape-changing bench in their day-to-day lives.

3. Designing and Implementing Interactions

The premise of the field of TEI is that technology can be embedded into any physical object or material, which creates many opportunities for exploring different ways to enable human-computer interactions. This includes off the body and on the body, through one object or multiple objects, by touch or by gestures, with surfaces and within space, and many more. TEI also draws on and fuels a variety of technological developments to support interactions that connect the physical and digital worlds. This section reviews opportunities for interactivity along with different kinds of supporting technologies (Section 3.1) as well as the design tools and processes used to create them (Section 3.2).

For an overview of haptics and tactile interaction, please see Chapter 5 in this volume, and for wearable interaction, see Chapter 10.

3.1 Interactivity and Technologies

In the previous section, we reviewed some of the frameworks that have served to map out the TEI design space. While many of these operate at a conceptual level and do not directly point to specific forms of interactivity or to the technologies that support them, two frameworks that provided early perspectives on interactivity include Ullmer and Ishii’s (2000, 2001) categorization of tangible interfaces into spatial, constructive, and relational systems, and Shaer et al.’s (2004) TAC paradigm that focused on interactive tokens and the constraints within which they can be manipulated. The focus in both these frameworks was on tangible interactions and interfaces, not on embodied interaction, which is in line with the early developments in the field. TEI was at first intended to stand for *Tangible and Embedded Interaction*, emphasizing the idea that computation can be embedded into physical artifacts to create tangible interfaces. *Tangible and Embedded Interaction* was also the initial name of the TEI conference that was held for the first time in 2007. The conference acronym “TEI” was subsequently (in 2010) changed to represent *Tangible, Embedded, and Embodied Interaction*, highlighting the fact that beyond tangible and embedded computing, the growing field was increasingly considering a broad range of embodied interactive forms and technical solutions. In this chapter, as well as in general within the TEI research and design community nowadays, “TEI” is typically taken to mean *Tangible and Embodied Interaction*, with the idea that embedded computation is implicit within the term and is used as a technical solution for the creation of many tangible systems.

In this section we draw on the Responsive Objects, Surfaces, and Spaces (ROSS) framework and toolkit (Bellucci et al., 2016; Wu et al., 2012) to illustrate interactivity in different forms and at different scales. However, we expand this organizing framework to consider on-the-body interaction as well. It is important to note that these are not distinct categories, but rather approaches that often work together in interactive ecologies that can include different combinations of people, objects, surfaces, and spaces. Indeed, the ROSS framework was later reimplemented, expanded, and renamed to the Responsive Ecologies Toolkit (RE/Tk) (Tarun et al., 2016) to highlight the potential for connections and interactions between different types of objects, surfaces, spaces, and people at different scales. This relates to a broader area of work in the HCI community on cross-device interaction, which has been nicely surveyed by Brudy et al. (2019). Within each of the areas – objects, surfaces, spaces, and people – we illustrate the possibilities for interactivity through numerous examples and describe some of the underlying technical solutions. We also give examples of interaction opportunities that connect across these areas. As an exhaustive survey of interactive approaches and technical solutions is beyond the scope of this chapter, we refer readers to the book *Weaving Fire Into Form* (Ullmer et al., 2022) for a more in-depth discussion, and particularly to the chapter on "Mediating Technologies" where the different technologies for sensing, display, actuation, and communication are described in greater detail.

Objects: Physical objects offer many opportunities for digital interactivity based on the way they are grasped, manipulated, and tracked. This includes detecting their presence and position/orientation within space or on a surface such as a table or floor; detecting the way we grasp or touch them such as tapping, pinching, or stroking; detecting the movements or gestures that we make with them such as tilting, flipping, or shaking; and detecting various relationships between them such as neighboring, stacking, and containment.

A classic example of a tangible interaction device is the Marble Answering Machine concept, described in Section 2.3, that was proposed by Durrell Bishop in 1992 while he was a student at the Royal College of Art in London (Crampton-Smith, 1995). In the Marble Answering Machine, physical marbles represent messages, which roll out of the machine along a track when they are received. They can then be picked up and dropped into a small indention to be played back, and subsequently dropped into a chute to be deleted, which allows the marbles to recycled for new messages. Bishop's work addresses a key question for TEI design in asking how the properties of physical objects can represent their role and the state of interactive systems (see Durrell Bishop's vignette in *Weaving Fire Into Form* (Ullmer et al., 2022)). While the Marble Answering Machine is a custom designed everyday object, other research in TEI has looked at how ordinary everyday objects can be augmented to create tangible interfaces. Examples include the musicBottles (Ishii et al., 1999) and genieBottles (Mazalek et al., 2001), in which physical glass bottles were used as containers for digital (audio) information, either music or stories, that were released upon opening the bottles (see Figure 3, left), as well as the DataSpoon (Zuckerman et al., 2016) for monitoring the kinematics of children with motor disorders when self-feeding. Like many tangible interfaces, these objects are equipped with sensors to enable digital interactions -- electromagnetic tags and a swept-frequency resonant tag reader (J. Paradiso & Hsiao, 1999) to detect the opening and closing of the bottles and an IMU (inertial measurement unit) Arduino board to detect movements with the spoon. Other opportunities for interactivity include the creation of replicas, for example by 3D printing. Examples include augmented replicas of historical everyday objects for interactive museum experiences, such as 16th century prayer nuts (Chu et al., 2016) (see Figure 3, right) and WWII artifacts (Marshall et al., 2016).

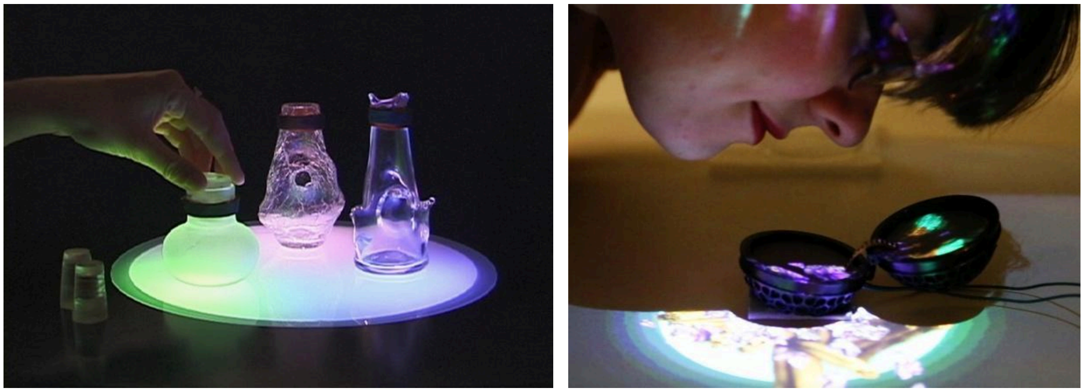

Figure 3: *The genieBottles system demonstrated an interactive audio-based story that was told through the monologues and dialogues of three genies who were released when a user opened the bottles (Mazalek et al., 2001) (left). 3D printed replicas of 16th century prayer nuts were used to created multisensory interactive museum experiences (Chu et al., 2016) (right). [ALT TEXT: The left-hand photo shows the genieBottles system, which consists of three glass bottles that contain genies who tell stories. A user releases one of the genies by opening its bottle. The right-hand photo shows a 3D printed prayer nut. A user has opened the prayer nut and is leaning in to smell its fragrance while the tabletop underneath displays visual information about the fragrance contained inside.]*

Beyond everyday objects, researchers have also explored the creation of custom-designed articulated objects with sensors to detect the movement of parts, such as the puppet interfaces designed for tangible and embodied gaming (Mazalek et al., 2011), machinima creation (Mazalek & Nitsche, 2007), and interactive storytelling (Echeverri, 2022). Articulated tangible objects can also be modular like Topobo (Raffle et al., 2004), a tangible system for building robotic creatures that can record and playback physical motion. For Topobo, servo motors with sensor and drive circuitry were used for sensing and actuation. Some custom-built tangibles have included on-board display capabilities, such as the Siftables (Merrill et al., 2007), which were later commercialized as Sifteo Cubes. Multiple cubes could be spatially arranged on a flat surface, tilted, tapped, and bumped, with the display screen providing real-time visual feedback. Actibles (East et al., 2016) expanded the Sifteo concept by also allowing stacking interactions and by providing feedback about adjacency and stacking via an LED ring around the device (DeLong et al., 2019). Some researchers also explored the use of Sifteo cubes and Actibles as tangible controls on interactive surfaces, such as in Active Pathways (Mehta et al., 2016) and Tangible BioNets (Manshaei et al., 2019).

Some tangible interactive objects have explored the use of different materials, such as the interactive sweatshirt, handbag, and hat created by children using the Lilypad Arduino (Buechley et al., 2008). Designed for e-textile and wearable projects, the Lilypad has been widely adopted in the TEI and maker communities. Tangible object explorations have also included natural materials such as water (Dietz et al., 2006), soap bubbles (Sylvester et al., 2010), trees (Coffin, 2008), clay (Piper et al., 2002), and sand (Beckhaus et al., 2008; Ishii et al., 2004; Kegel & Hemmert, 2019). Some of these efforts have been characterized as ephemeral user interfaces (Döring et al., 2013) and deformable interfaces (Boem & Troiano, 2019). While some of the sand-based interfaces like SandScape (Ishii et al., 2004) and GranuleSynthese (Beckhaus et al., 2008) focus on user interactions with sand, providing top dop projection onto user-created sand formations, others like the SandExplorer (Kegel & Hemmert, 2019) create sand sculptures as a form of physical data display, or “data physicalization” (Jansen et al., 2015), using a semi-manual plotting mechanism. This latter approach relates to the vision of “radical atoms” (Ishii et al., 2012), in which shape changing materials can enable tangible objects to take on different forms in response to user interactions. For example, coMotion (Kinch et al., 2014) is a shape-changing bench, which creates surprising, amusing, or sometimes awkward experiences when users find they have been lifted or pushed together as the bench communicates its intentions by changing its physical form.

Surfaces: Many TEI systems have explored the use of various surfaces (tables, walls, floors) for user interaction, often in combination with tangible objects as mentioned above. Tabletop systems in particular have received a lot of attention from the TEI community, with both tangible objects and direct touch serving as input for the tabletop display surface. Early tangible tabletop systems used reflective markers with an overhead camera for object tracking and provided a top-down projected display. This can be seen in Illuminating Light (Underkoffler & Ishii, 1998) and Urp (Underkoffler & Ishii, 1999), which were used for simulations in holography and urban planning, respectively. In both cases, the tracked tangible objects were designed to physically represent their role in the system, such as optical lenses, building models, and different kinds of tools. As a user’s hands could interfere with the object tracking and display, subsequent approaches explored how to embed the sensing technology into the tabletop, for example using electromagnetic tags and an antenna grid in the tabletop for tracking objects. This was coupled with overheard projection, as seen in the Sensetable (Patten et al., 2001) and Tangible Viewpoints (Mazalek et al., 2002) systems. The TViews Table (Mazalek et al., 2006) also moved the display below the tabletop surface by using an acoustic-based sensing approach that tracked tangible objects using sound waves transmitted through a plate of glass placed above an LCD screen. While these examples focused on tabletop tangible interactions alone, the reacTable music performance system (Jordà et al., 2007) combined tabletop tangible and multitouch interactions (see Figure 4, left). The reacTable was developed in conjunction with an open-source development toolkit that was widely adopted by the TEI community, as seen in projects such as the Architales art gallery installation (Mazalek et al., 2009) and the Mapping Place museum exhibit (Chu et al., 2015a) (see Figure 4, right). The toolkit consisted of the reacTIVision framework and the TUOI protocol (Kaltenbrunner, 2009; Kaltenbrunner & Bencina, 2007), which together enabled the tracking of finger touches as well as tangible objects tagged with fiducial markers on a rear-projected tabletop display. Eventually commercially available solutions such as the tangible and multitouch displays by MultiTaction became available, enabling the creation of tangible tabletop systems such as the BacPack bio design museum exhibit (Loparev et al., 2017) as well as tangible multi-surface (tabletop and wall) systems such as Tangible BioNets (Manshaei et al., 2019) and Tangible Chromatin (Manshaei et al., 2022).

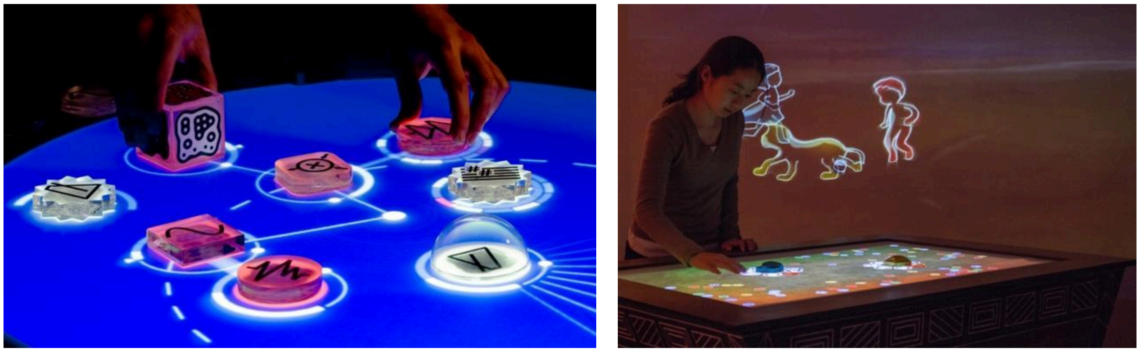

Figure 4: *A user interacts with tangible objects on the reacTable music performance system* (Jordà et al., 2007). *The reacTable was created by Jordá, Kaltenbrunner, Geiger, and Alonso. Photo: Xavier Sivecas (left). A museum visitor creates stories using multitouch and tangible tabletop interactions in the "Mapping Place" museum exhibit (Chu et al., 2015b) (right). [ALT TEXT: The left-hand photo shows a user interacting with two tangible objects, one in each hand, on the reacTable music performance system. The right-hand photo shows a museum visitor arranging virtual beads around a tangible shell on an interactive tabletop surface in the "Mapping Place" museum exhibit.]*

Researchers have also explored tabletop surfaces with actuated tangible objects, such as the Actuated Workbench (Pangaro et al., 2002) which used magnetic forces to move objects on a tabletop display surface. It is also possible for an entire tabletop surface to be actuated, such as with inFORM (Follmer et al., 2013), TableHop (Sahoo et al., 2016), and the inflatable hemispherical display (Stevenson et al., 2010). The inFORM system used an array of actuated rods to transform the geometry of a physical surface, allowing it to lift, translate, or rotate objects that are placed on it. Both TableHop and the inflatable hemispherical display used flexible surfaces (spandex in the former and latex in the latter). The TableHop fabric surface was actuated using electrostatic force and a graphical display was rear-projected onto the surface. The inflatable hemispherical display, which was also rear-projected, made use of air pumps to inflate the surface to different levels and users could pinch the surface or press their fingers into it.

Opportunities for tangible and embodied interactions also include the surfaces in everyday built environments, such as windows, climbing gym walls, floors, and even buildings. For example, Paradiso et al. (2002) developed an acoustic-based sensing system for detecting knocks and taps on a large sheet of glass, which was then used to develop interactive shop windows and gallery displays. Several projects have also augmented indoor climbing walls, for example using climbing holds with embedded sensors and LEDs in the DigiWall (Liljedahl et al., 2005) or using a Kinect sensor and projected display in the Augmented Climbing Wall (Kajastila et al., 2016). Researchers have also explored floor-based interactions and interactive floors for engaging full bodies in interaction with digital media. For example, the StoryMat (Ryokai & Cassell, 1999) was a children's playmat that could record and recall children's storytelling activities through audio and overhead projection as they played on the mat with wirelessly sensed stuffed toys. Other systems that encouraged embodied physical play for children include the iGameFloor (Grønbæk et al., 2007) and MEteor (Lindgren et al., 2016). The iGameFloor was a bottom-projected interaction floor with computer vision tracking of user movements that was installed as a full-body gaming platform in a public school, while MEteor was a top-projected interactive floor that allowed children to learn about gravity and planetary motion through embodied (full-body) interaction with a floor-projected simulation. The GravitySpace (Bränzel et al., 2013) system used a bottom-projected pressure-sensitive floor to track both people and objects. The system was able to determine objects and events above the surface, including a user's center of gravity and pose, as well as different types of weighted furniture. Other work has also looked at ergonomic interaction on touch floors (Schmidt et al., 2015), arguing that users should be able to interact in a variety of poses, including sitting and lying down, to avoid strain from prolonged standing and looking down. Lastly, it is worth mentioning the opportunity of transforming large-scale architectural surfaces into media façades for public engagement (Caldwell & Foth, 2014). In some cases, these media façades make use of tangible and embodied interaction approaches, such as in the SMS Slingshot and Spread.Gun (Fischer & Hornecker, 2012). These were both projective devices (a cannon and a slingshot) with which user-composed text messages could be shot onto the façade of the building using familiar physical interaction mechanisms (a trigger and a rubber band).

Spaces: The object and surface interactions described above all take place within physical space, even though space itself is not necessarily part of the interactive experience. However, many researchers have also explored how to incorporate 3D space into tangible and embodied interactive experiences, for example by sensing full-body interactions using computer vision, or by displaying 3D content using augmented reality (AR) or virtual reality (VR). It is important to note that there is significant overlap between the surfaces and spaces categories, as interactive spaces often use surfaces like interactive floors to detect full-body user interactions, and both floors and walls to display digital content. Here we focus on opportunities for interactivity that have not been covered in the previous sections.

Many embodied interaction experiences make use of computer vision for detecting user's full body movements in space, sometimes in combination with tangible object interactions. An early example was the KidsRoom (Bobick et al., 1999), a fully interactive room that was equipped with four cameras, video projection on two walls, a microphone for audio input, four speakers for audio output, and a moveable bed. The overhead camera was used to locate people and the bed, while two of the other cameras were used to detect the actions performed by people in the room. Other researchers have demonstrated how comparatively simple setups can be used to create embodied interactive experiences. For example, Tangible Comics (Samanci et al., 2007) was a single projection full-body interactive storytelling environment in which a single webcam was used to capture a user's body movements and gestures, as well as interactions with tangible objects such as an umbrella, stopper, and flashlight. Other systems have explored embodied interaction using marker-based motion capture suits, for example in live dance performance (Clay et al., 2012), or depth cameras such as the Microsoft Kinect, for example in improvisational dance (Mentis & Johansson, 2013). Kinect sensors have also been used to detect the movements of hanging plants in an interactive installation (Triebus et al., 2021). In this case, visitors passing through the space interacted with the plants through direct touch or indirect means such as airflow. These interactions were tracked by the Kinect sensor based on changes in the plants' leaves.

Some interactions bridge physical and virtual space using head-mounted displays. The idea of Tangible Augmented Reality (AR) (Billinghurst et al., 2008) showed how users could interact with 3D virtual content using normal physical-world interactions by associating the virtual content with physical objects in the environment. Since that time, the decreasing cost of head-mounted display technologies has resulted in a proliferation of AR and VR research that explores how to create immersive experiences across the physical and virtual worlds. For example, Tangible VR (Harley et al., 2017) and Embodied Axes (Cordeil et al., 2020) use sensor-based tangible interfaces to interact with 3D content in VR and AR, respectively, while Teachable Reality (Monteiro et al., 2023) introduced a tangible AR prototyping tool that can make use of arbitrary everyday objects for user input. Many researchers have also explored the use of full-body tracking for VR, as in the E-WAFE system (Kalaitzidou et al., 2022), which used feet, waist, hands, and head trackers together with machine learning-based pose recognition for VR exergaming. Some researchers have also looked at how different sensory modalities, including smell, sound, taste, and touch, can be used to create embodied experiences in VR spaces (Harley et al., 2018). Finally, projects such as Uplift (Ens et al., 2021) have explored the creation of fully immersive environments for data analytics, combining 3D content in head-mounted AR with tangible interfaces and interactive tabletop and wall displays.

Bodies: In addition to objects, surfaces, and spaces for TEI, many researchers have explored the potential for on-the-body interaction. Much of this work relates to the area of wearable computing, such as augmented shoes and garments. Wearables are covered in detail in Chapter 10 of this volume, so we provide only a brief overview here.

Shoe-based systems include the GaitShoe sensor-augmented shoes for gait analysis (Bamberg et al., 2008) and the Music-Touch vibro-tactile shoe for hearing impaired dancers (Yao et al., 2010). The GaitShoe was embedded with a suite of sensors, including accelerometers, gyroscopes, force sensors, bend sensors, dynamic pressure sensors, and electric field height sensors, which together provided data for gait analysis using multisensor pattern recognition. The Music-Touch shoe used embedded vibrating motors embedded to communicate rhythm and tempo of music to hearing impaired dancers. Garment-based examples include memory rich garments that display their history of use (Berzowska & Yarin, 2005), dresses as dynamic digital displays (Kleinberger & Panjwani, 2018), and fashion-oriented assistive technology garments (Profita et al., 2015). These wearables provide interactivity in different ways, including textile-based sensors for touch, microphones for auditory input, accelerometers to detect movements, vibration motors for tactile output, as well as embedded LEDs and even small portable projectors for visual output. Some projects have moved beyond typical garments to explore wearable augmentations that can expand our bodily functions and expressions in diverse ways. Examples include the hipDisk musical disk-shaped hip augmentation (Wilde, 2012), the Monarch wing-shaped muscle-activated kinetic textile (Hartman et al., 2015), and the Arque prosthetic tail that alters a user's center of gravity as a body balance support mechanism (Nabeshima et al., 2019).

Researchers have also looked at the potential for using the body itself as an input and output for computer systems. For example, muscle-computer interfaces (Saponas et al., 2009) have used forearm electromyography (EMG) to detect different finger gestures and grips and the Skinput system (C. Harrison et al., 2010) used an armband with vibration sensors to detect and locate finger taps on the skin. Lastly, researchers have explored opportunities for the skin as a display surface. For example, OmniTouch (C. Harrison et al., 2011) and Armura (C. Harrison et al., 2012) both demonstrated on-body graphical displays.

3.2 Design Tools and Processes

Designing TEI systems requires a unique set of tools and processes that are specifically tailored to the nature of physical engagement and the integration of digital technology. In this section, the multifaceted landscape of TEI design is explored, highlighting the tools and processes that enable designers to create interactive experiences.

Discerning that TEI spans the real and digital worlds, Billinghurst et al. (2010) discussed how tangible interaction techniques can be intertwined with Augmented Reality (AR) user interfaces. They provided design guidelines emphasizing three key elements that must be considered in the first place: (i) the physical elements of the system; (ii) the video and audio displays used; and (iii) the interaction metaphor that maps interaction with the real world. The interaction metaphor of bonding tangible interaction performed in the real world with a virtual or digitally augmented environment constitutes a fundamental principle that designers and developers should consider when implementing their applications. As Ishii (2008) stressed, although the tangible interaction enables physical embodiment to be directly coupled to digital information, it is limited to merely representing a change in material or physical properties. This can be compensated by utilizing pliable representations such as video projections and sounds to harness the tangible interaction results in the same space, thereby providing a dynamic expression of the underlying digital information and computation. Thus, TEI design tools and processes extend beyond software solutions alone. An integral component in TEI is the creation of digitally augmented physical environments that provide fundamental infrastructure and technological artifacts, and it is through this that the conceptualization, design, and implementation of TEI systems becomes possible. For example, the Illuminating Light design tool (Underkoffler & Ishii, 1998), one of the renowned works in the field, provides a digitally augmented tabletop enabling users to experiment with holographic layouts. Based on the same design concept, Underkoffler & Ishii (1999) introduced the Urp application for handling architectural elements in urban planning and design. This system follows the same design principles as the Illuminating Light, for attaching projected forms to physical architectural models, providing urban planners with more accessible computational resources in a manner that aligns with the spatial and geometric nature of their work. Despite the technology limitations of the time, these works unraveled many fundamental aspects of TEI design and shed light on many different research directions and efforts that followed. By exploring the concept of *luminous-tangible interactions*, key issues were addressed and eventually became a set of guiding principles. Beyond their professional applications, these works tap into the universal appeal of infusing everyday objects with added meaning and interactivity, making them an engaging tool for a variety of creative tasks, from physics simulations to design and more.

The technical solutions that support the implementation of TEI systems can be divided into two main categories: sensor-based technical concepts and computer vision algorithms (Krestanova et al., 2021). The sensor-based solutions include wireless technologies for facilitating the tangible components intercommunication, such as RFID tags, or Bluetooth modules, whereas WiFi or ZigBee standards are mostly used. A wide variety of sensors is met in TEI research works, such as optical sensors (e.g. IR) or Light-Dependent Resistors (LDR), mostly used for determining the relative position of tangible blocks, their rotation, or distance, as well as to detect any obstacles. Also, tilt sensors are used in the implementation of TEI systems, enabling the detection of object motion or the management of energy saving (e.g., the component is in deep sleep mode until it is taken by the user). Accelerometers, gyroscopes, and magnetometers are used for the detection of the components' motion, velocity, and trajectory. On the other hand, many approaches rely on Computer Vision and Image Processing algorithms to determine tangible objects’ properties in real-time, using cameras. These approaches can be clustered into two main categories, marker-based and markerless. In the first case, the systems recognize specific markers that are placed either in the environment or on tangible objects. Through these markers the system can detect and track the objects, calculating their position and location in the environment, making the system capable of perceiving and understanding tangible or embodied interactions. The markerless approaches analyze the interaction scene without relying on markers, using advanced image processing algorithms based on Machine Learning, such as instance segmentation (Hafiz & Bhat, 2020) or object 3D pose estimation (Arnold et al., 2019), to detect and track the objects of interest, specifying the same properties with the marker-based approaches.

As mentioned above, the existence of software and technical solutions facilitating the design, prototyping, and eventual delivery of TEI systems is important, as researchers and designers can avoid doing everything from scratch. To that end, there exist numerous tools, frameworks, and development environments aiming to help designers and developers of TEI systems. For example, the InPrinted framework (Margetis et al., 2019) is a versatile tool that aims to enhance paper interaction within intelligent environments. It enables users to naturally engage with printed materials and offers a range of context-aware features for incorporating digital augmentation into printed content. InPrinted offers several methods for finger-based interactions, such as pausing to select or double-click, using hand shapes to signal actions, drawing simple shapes, moving hands to trigger specific actions, and employing two-handed gestures for resizing annotations. Stylus-based interactions support handwriting techniques for annotating printed materials, with fundamental scope selections inspired by traditional manuscript marks. Finger-based interactions provide a tactile and dynamic approach, while stylus-based methods excel in legibility and usability for handwriting tasks, creating a rich palette of natural interactions. InPrinted supports various AR approaches, such as projection-based augmentation, and companion displays to blend digital content with the real world. It addresses challenges in device independence, application deployment, and interaction design, making it a comprehensive framework for augmented printed materials. One of the practical applications of the InPrinted framework is the Interactive Maps system (Margetis et al., 2017), which facilitates interaction with printed maps and effectively integrates digital information. An in-situ observation experiment demonstrated the ease and naturalness of interacting with augmented paper, ultimately resulting in a positive user experience.

Another recent approach to designing and implementing TEI applications is through Tangible Touch (Potts et al., 2022). This toolkit utilizes capacitive sensing and allows for quick prototyping and exploration of tangible cubes. The exchangeable capacitive panels enable touch-based gestures and interactions that can be used for tangible input in virtual reality, augmented reality, or physical computing. The authors provide three different example applications employing the toolkit, showcasing its featured functionalities. The two applications (a platform game and a media player) highlight the potential of the toolkit in two different domains. However, the first application uses the tangible cube of the toolkit to manipulate the rotation and scale of 3D meshes, which are incorporated into a 3D engine environment. This way, a developer can easily assess the mapping of the provided tangible interaction metaphors with the real world, at development time. SPATA (Weichel et al., 2015) is another tool that combines two spatial measurement instruments with virtual design environments, simplifying and enhancing the design process for fabricable artifacts in digital spaces such as mechanical computer-aided design, mesh-based modeling, and 2D design. With SPATA, designers can create and manipulate objects by transferring physical measurements from existing objects to design software, allowing for seamless transitions between the virtual and physical environment. SPATA offers intelligent features such as orientation sensing, real-time information display, and built-in controls, providing designers with a convenient and integrated design experience. This makes it a valuable asset for designing objects intended for the physical world.

Constructable (Mueller et al., 2012) is an example of how TEI can be used in the design and prototyping process. It is an interactive drafting table that allows users to produce precise physical output at every step. Users draw directly on the workpiece using a handheld laser pointer. The system tracks the pointer and uses a fast high-powered laser cutter to cut the workpiece along the path of the sketch. Constructable ensures precision through tool-specific constraints, user-defined sketch lines, and the use of the laser cutter itself for all visual feedback instead of using a screen or projection. Constructable has been shown to enable users to create simple yet functional devices, including a simple gearbox that is impossible to create using traditional interactive fabrication tools. MARCut (Kikuchi et al., 2016) is another tool for personal fabrication that uses a laser cutter to simplify the way designs are executed on physical objects. Unlike traditional methods, MARCut follows a physical marker-based process that allows for interactive fabrication with both tangible and CAD-based design elements. By placing markers directly on the object, the system streamlines the laser-cutting process, reducing complexity, and operation time, while enhancing user understanding during design specification and alignment. Apart from cutting and engraving, MARCut also supports various operations such as adjusting laser parameters for different materials, copying shapes to other surfaces, setting operation order, and CAD model alignment. The key contributions of this approach include a marker-based technique for tangible interactions, markers that provide the laser cutter with multiple parameters, and a vision-based system for precise alignment and instant creation on existing objects.

4. Exploring and Experiencing Applications

This section takes a human-centered perspective to look at how TEI can be applied to different areas of the human experience, ranging across education, health and wellbeing, design, storytelling, and more. While the list is not exhaustive, we aim to show the breadth of TEI application areas covered in research.

4.1 Learning and Education

Children's *learning and development* is one of the most studied application areas in Tangible and Embodied Interaction, because of the benefits of the combination of interactivity -- embedded technology responding to user actions -- with physicality. These benefits include the fact that TEI can support cognitive processes and development, can encourage initiative-taking and thinking outside the box, can support communication and collaboration, and is suitable for beginners (for a comprehensive review, see Liang et al., 2021). The most popular learning activities represented in TEI studies are storytelling and programming (Li et al., 2022; Liang et al., 2021).

Iconic examples include early *educational TEI toys*, such as Curlybot (Frei et al., 2000), which allows young children to play with mathematics and computation through a robot that draws patterns by repeating the physical movements that children make with it. Another iconic kinetic robot toy is Topobo (Raffle et al., 2004), which consists of robotic building blocks that can form a creature that teaches children about locomotion and movement.

For primary school children, the *classroom* is an obvious context to design for and this has resulted in numerous applications that have aimed to support students in their learning. Examples include Tern, a tangible computer programming toolkit evaluated in a classroom, museum, and summer camp (Horn et al., 2012), and MoSo, a tangible system for children learning abstract sound concepts, such as pitch, volume, and tempo (Bakker et al., 2012). The Book of Ellie (Papadaki et al., 2013) is another example of first-grade elementary school pupils interacting with physical objects to learn the Greek alphabet and proceed with their first steps of learning to read. The system combines both physical books and cards with electronic media to enable young pupils to interact with a virtual character, Ellie, who helps them learn Greek letters and how to read.

Some systems have focused on supporting teachers as well as students. Examples include the FireFlies toolkit (see Figure 5), which aimed to support communication between the teacher and their primary school pupils and offload cognitive processes for the teacher (Bakker et al., 2013; Verweij et al., 2017), and the Tangible Lighting Proxies toolkit, that can be used to teach and learn practical skills to high school students, in particular around stage lighting (Nicholson et al., 2021).

While most of the tangible learning research to date has focused on children, Li et al. (2022), in their meta-analysis of tangible learning studies, suggest to focus future studies more on tangibles for teachers, on the social and emotional impact of tangibles on students, and on the meaning and metaphors of tangible interaction.

Figure 5: *The FireFlies system includes light-objects that can be illuminated in different colors (Bakker et al., 2013) (left) and that serve as a peripheral visual display of information in the classroom (right). [ALT TEXT: On the left side a grid of four images shows the FireFlies light-objects lit in four different colors: yellow, blue, red, and green. The photo on the right shows four FireFlies light-objects lit in either red or green on children's desks in a classroom while children sitting at the desks are working.]*

4.2 Discovery and Problem Solving

Aside from the classroom, the museum setting is another popular educational context for TEI, especially because museums often already use physical objects and artefacts for visitors to touch and interact with. Adding technology is a logical next step, for example through the use of smart replicas (Marshall et al., 2016), which are copies of artefacts on display, but with added technology (e.g., sensors, RFID tags or NFC) that can activate a response, typically when used at certain indicated locations in the exhibit.

The museum setting, where people are free to look at and interact with exhibits in the way they like, is particularly suitable for studying the advantages and disadvantages of interaction styles by comparing different designs. For example, in comparing a tangible user interface with a graphical user interface by using physical and virtual objects in an exhibit, Ma et al. (2015) showed that some factors were the same, such as the questions asked and the facilitation of social interaction. However, for some variables TEI scored better, including the affordance for touch and manipulation, which resulted in people staying at the exhibit longer. These findings were confirmed by Horn et al. (2020), who found that the tangible interface attracted and engaged visitors more than the multitouch interaction style but there was no difference in how they supported collaborative interaction. Grote et al. (2015) also compared multi-touch and tangible interaction, and found advantages and disadvantages when interacting with large datasets for both. For example, TEI was useful for simple representations of complex structures and rules, while a challenge for TEI in general was scalability, which is especially pertinent when working with large datasets. Compared to multitouch, the tangible components had the advantage that they could be used beyond the limited interactive screen space and were less subjected to the problem of occlusion.

When comparing tangible interaction with a bespoke phone app in a museum exhibition, Petrelli and O'Brien (2018) again confirmed that people prefer the physical over the digital for its interaction style, while the phone was preferred because of its mobility. The latter seemed to support more roaming museum visitors, while the physical supported visitors that were after more in-depth knowledge of the exhibit. Instead of designing and then comparing different interfaces, Hornecker (2010) observed existing museum exhibits and compared their interaction styles and visitor usage. She found that one main factor that determined usage was whether it allowed for multi-user participation and thus social interaction, which a well-designed tangible user interface can support well.

Another group of TEI museum studies has focused on allowing visitors to discover and learn about specific topics; STEM, in particular, is well-represented. For example, Horn et al. (2008) showed that tangible interaction was inviting and engaging in teaching children how to program a robot's movements using wooden physical blocks that click together like jigsaw puzzle pieces. Grote et al. (2015) designed an application to teach visitors about bio-design, the activity of creating new synthetic organisms, combining engineering and biology.

Other researchers have looked at how TEI systems can support scientific *discovery* in a research and laboratory setting. For example, work by Tabard et al. (2011, 2012, 2013) involved the design of an interactive lab bench that included a multitouch tabletop with tangible interaction. Interestingly, one of the findings for this particular setting was that biologists wanted to reduce non-essential tangible objects to declutter the actual bench space (Tabard et al., 2012), which already had physical objects that were part of the workflow and needed to be physical, such as racks with test tubes. Tangibles and interactive surfaces can also support *sensemaking* around large biological datasets. For example, Tangible BioNets (Manshaei et al., 2019) used active tangibles (i.e., physical objects with embedded sensing and display capabilities) in combination with multiple displays of different scales to support visualization and analysis of large biological networks (see Figure 6, left). They noted that in working with large datasets, it was important to decide which parts of the data should be assigned to tangibles. Working closely with biomedical engineering experts to analyze their workflows, the researchers identified key workflow aspects that were best served by tangible interactions. They noted that the concept of tangibles as "containers" for data, as well as the ability to assign and re-assign tangibles to different functions, were important design strategies for reducing the number of tangibles required when working with large datasets. Researchers have also explored how tangible interfaces can also be used in *model-building*, such as constructing biological models. Physical models have been used to help scientists think through and visualize their ideas throughout history, with a well-known example being Watson and Crick's model of DNA. Modeling kits consisting of small balls and sticks have also been used in chemistry education and research. Tangible interaction approaches can further enhance these kinds of models, for example by using spatial tracking techniques to augment 3D printed molecular models with dynamic properties, as in the work of Gillet et al. (2005). Tangibles can also be used in constructing models of dynamic systems, such as in the Active Pathways biological network modeling system (Mehta et al., 2016). In this work, Sifteo Cubes were used to represent molecules, and touching two cubes together created a reaction between them (see Figure 6, right). The cubes could also be used to dial in parameters, such as molecule concentration or reaction speed. A modeler was thus able to build up a complex reaction network through simple physical actions, while the system generated the corresponding computational model and visualized it on an interactive tabletop display. The system was tested with pairs of novice modelers and proved successful at supporting collaboration and understanding of complex systems. At the same time, the researchers found that users had prior expectations for the system based on their experience with smartphones and smartwatches, and that the lack of a multitouch display on the Sifteo Cubes was perceived as a limitation. This led the researchers to note the importance of striking the right balance between providing novel vs. familiar interaction approaches for the active tangibles.

Figure 6: *Tangible BioNets was a multi-surface system that used stackable active tangibles together with interactive tabletop and wall displays to support visualization and analysis of large biological networks (Manshaei et al., 2019) (left). In the Active Pathways system, a user could touch together two Sifteo cubes representing molecules to create a reaction between them, which was visually represented on the tabletop surface (Mehta et al., 2016) (right). [ALT TEXT: The left-hand photo shows a user stacking one active tangible on top of another on an interactive tabletop surface. The results of this interaction are displayed on an adjacent interactive wall display. The right-hand photo shows a user touching together two small cubes with displays that represent molecules to create a reaction between them. The resulting change in the biological reaction network is shown on a tabletop surface below the cubes.]*

4.3 Health and Wellbeing

The health and wellbeing application area is well-represented in TEI research, and even already in some commercially available applications (for an overview, see Section 2.3 in Ullmer et al., 2022). Of course, supporting health is relevant and useful for large groups of people, and tangibility has advantages for specific use cases, such as situations in which physical objects already play an important role. In these cases, it can be a straightforward next step to add technology into objects, as shown in the context of rehabilitation and physiotherapy. For example, scraping is a technique in physiotherapy where a physical object is used to move over a client's body, and this object can be enhanced with sensors to provide the physiotherapist with feedback on the amount of pressure used on a patient (Walker et al., 2020).

Stroke rehabilitation is known for the use of basic physical objects, its repetitive exercises, and the fact that patients have difficulty to stay motivated. As such, it is an application area that has interested TEI researchers and even led to design recommendations (Magnusson et al., 2017). One example is a design called Balance Tiles (A. J. Bongers et al., 2014; Donker et al., 2015), which consists of a set of floor tiles that fit together like puzzle pieces, which can be combined to facilitate a variety of balance exercises for stroke patients in a hospital's rehabilitation ward. Other examples are tangible games for exercising upper limbs, such as the Lights Invader game (Wang et al., 2017), focusing on hand movements, and the Catching Seafood game (Bu et al., 2022) which aims to practice finger gripping, hand grasping and arm reaching. The ActivSticks (Kytö et al., 2018) is a tangible design that is intended for patients to use at home, instead of rehab, and to practice using both hands at the same time, as opposed to focusing on the side that is most affected by the stroke.

As discussed in Section 4.2, TEI is especially suitable when designing for children, and this extends beyond learning in classrooms and museums to health and wellbeing in hospitals and homes. For example, work-in-progress by Warren (2019) explores the potential of social tangible technologies to support young cancer patients in hospital. Other work has investigated tangibles for children with ADHD, such as ChillFish (Sonne & Jensen, 2016), a breathing device and application designed to calm children down, and TangiPlan (Weisberg et al., 2014), a system consisting of a number of physical objects in relevant locations to help remind children of their morning routines. All three of these examples are in early stages and have not yet been evaluated in situ.

TEI research has also looked at the tracking and communication of data related to health and wellbeing. For example, Pakanen et al. (2021) developed a tangible pollen allergy tracker that allows people to self-track their symptoms and medication use, by pressing buttons on a keyring device that communicates with a phone app which links this self-reported information to location, date, and time. These logs can be used by a medical professional and/or for research purposes. TEI can also be used to facilitate the communication of health-related information. For example, Guribye and Gjøsæter (2018) created a tangible hand-held stone-shaped object that patients can squeeze in order to communicate with their dentist during treatment. The squeezes are transformed into haptic feedback on the dentist's wrist, through an off-the-shelf smartwatch. Another project by Fyhn and Buur (2020) looked at how pain scales can be made tangible, by working with young adults who suffer from chronic pain and letting them express their pains through material manipulations. These were then shared with others and seemed to be effective in communicating the types of pains they were experiencing. A final example by Claes et al. (2015) created casual health-data information visualizations evaluated in a hospital waiting room, both in tangible form (using Sifteo displays) and as a graphical user interface. There was a preference for the tangible form because it allowed for more personal and reflective insights, while the GUI was preferred for efficiency reasons.

All the above examples focused on physical health, and only limited studies have investigated supporting mental health. Vianello et al. (2019) explored how TEI can support people in mindfulness practice, by introducing the TANGAEON system, which is an extension of the AEON mindfulness mobile app (Chittaro & Vianello, 2014) with an interactive, water-filled glass container. The study results indicated that incorporating a natural element in tangible interactive practices, as seen in TANGAEON, enhanced user engagement and focus during mindfulness. On the same wavelength, Daudén Roquet et al. (2022) investigated the effectiveness of an interactive tangible device that was designed to provide emotional support for children and youth during challenging situations. The device offered accessible and in-the-moment support, helping participants cope with emotional difficulties. The study included two deployments with adolescents and university students, and the qualitative data revealed that participants found the device helpful due to its soothing and grounding interactions. The findings suggest that interactive tangible devices can be innovative tools for providing embodied and situated support in mental health interventions for youth. This could bridge the gap between physical and cognitive strategies for emotion regulation.

Jingar and Lindgren (2019) discuss an approach for supporting humans with stress-related exhaustion to cope with their daily activities. The objective of this study was to investigate how diverse individuals approach the task of crafting their own tangible interfaces to convey emotions with a digital companion, examining the various preferences and expectations involved. The study interviewed six participants who were engaged in a co-creation workshop where they designed tangible prototypes. The results revealed that different users envision their tangible user interface differently, and the behavior of the interface is based on their preferences and experience. Therefore, a major challenge that needs to be addressed is the creation of tangible user interfaces that can fit the preferences of the users and adapt to their behavior.

4.4 Communication and Storytelling

TEI facilitates storytelling by allowing users to physically manipulate objects or engage in bodily movements that directly contribute to the narrative, making it a deeply engaging and participatory experience. While TEI enhances communication by enabling non-verbal expressions and gestures to convey information and emotions in a more natural and expressive manner, it also aids in remembering by leveraging the principles of embodied cognition (Wilson, 2002), where the physical actions and interactions with tangible interfaces can lead to more vivid and lasting memories. In this way, TEI proves to be a powerful tool for bridging the gap between humans and technology, fostering creativity, and enhancing our capacity for narrative immersion, effective communication, and memory retention.

Figure 7: *Wobble is a cone-shaped digitally augmented physical object that supports reminding in the home environment (Zekveld et al., 2017). [ALT TEXT: The photo shows the cone-shaped Wobble prototype sitting on a tabletop surface.]*

Remembering is a process in which an individual recalls past events using strong relations between concepts stored in memory. However, recollecting these relationships is very often not plausible since they change over time or are forgotten. Autobiographical memory is a type of human memory that is often used for everyday remembering (van den Hoven & Eggen, 2008), and that can be augmented by digital systems that, for example, include cues to initiate or facilitate the memory reconstruction process (van den Hoven, 2014; van den Hoven & Eggen, 2014). Physical objects, such as souvenirs that are part of a tangible system (van den Hoven & Eggen, 2003), can link to people's memories in several ways (van den Hoven et al., 2021), and this knowledge can be used to inform the design of tangible interaction for remembering. Some research has investigated tangible interaction toward supporting the prospective memory of individuals in the periphery of their attention. For example, Wobble (Zekveld et al., 2017) is a digitally augmented physical object that supports the tangible creation of prospective memory cues according to the users' location and time (see Figure 7). The authors used Wobble to investigate how peripheral reminders, which are noticed when an individual is ready to perform the task the reminder was set for but easily dismissed when they are occupied with other activities,

increase the likelihood of completing an intention while minimizing the frequency of being disturbed by reminders, which can cause annoyance and frustration. Mols et al. (2020) presented a study exploring open-ended reflection via the design and assessment of three different tangible concepts for reflective media interaction: Balance, Cogito, and Dott. Through this study, the researchers discovered that the effectiveness of these concepts depends on individuals' personal habits and the opportunities that arise from them, which can influence the potential for triggering reflection. The authors suggest that reflection can be supported during the creation process itself, rather than solely relying on system-generated or collected data for reflection. Moreover, reflection, especially within the home environment, requires consideration of the context and potential triggers, while open-ended reflection in everyday life is not necessarily structured but rather flexible, calling for further research into how longitudinal use can enhance the exploration and integration of reflection over time.

Another dimension that TEI can leverage is communication by allowing individuals to use physical objects and bodily gestures as intuitive means of conveying information and emotions, such as tangible gesture interaction (van den Hoven & Mazalek, 2011). This approach bridges the gap between human expression and technology, supporting more natural and expressive forms of communication, facilitated through the tangible gesture interaction framework (Angelini et al., 2015). An early example of touch-based remote communication can be seen in the Synchronized Distributed Physical Objects introduced by Brave et al. (1998), which employed telemanipulation to create the illusion that distant users were interacting with shared physical objects. The authors discussed two prototype systems that explored the concept of Synchronised Distributed Physical Objects. These systems allowed remote users to collaborate in a shared physical workspace by manifesting the presence of others through the movement of shared objects. One of the systems, inTouch, enabled haptic communication across distances. This concept extends the "What You See Is What I See" (WYSIWIS) principle from digital to physical spaces. Synchronized Distributed Physical Objects represent Physical WYSIWIS, where users can see each other's actions with shared objects, while in the inTouch case, "What You Feel Is What I Feel" also applies. This concept has provided a valuable guide for designing distributed Tangible Interfaces. Since then, several similar approaches have been explored for facilitating communication through TEI. Examples include LumiTouch (Chang et al., 2001), an emotional communication device that could seamlessly transition between passive and active modes, the Tangible Message Bubbles (Ryokai et al., 2009), through which youngsters could express and record their everyday expressions, play with these original recordings, and share these personal creations with their friends and family using natural interaction with tangible objects, as well as the educational applications facilitating the use of physical printed paper toward leveraging communication and the learning process in the classroom (Margetis et al., 2015).

Sharing experiences and telling personal stories to other people is an innate human need and a fundamental means of communication. To that end, several approaches explored the potential of using natural interaction with physical objects or tangible and embodied interaction as the ground for creating digital systems that facilitate human storytelling. Early examples include Triangles (Gorbet et al., 1998) as well as Tangible Viewpoints and Tangible Spatial Narratives (Mazalek et al., 2002; Mazalek & Davenport, 2003), which focused on navigating non-linear and multi-viewpoint/spatial interactive narratives, respectively. Triangles used modular tiles that could be snapped together in different configurations to explore a story, while Tangible Viewpoints and Tangible Spatial Narratives were built as a digitally augmented tabletop on which users could place their own pawns to interactively build and share their stories with others (see Figure 8). The Tangible Viewpoints and Tangible Spatial Narratives systems were used in two collaborative storytelling workshops in which participants took part in repeated cycles of story production and cooperative sharing, allowing them to evaluate their developing story lines in relation to the overall tale of their community. In more recent work, Echeverri and

Wei (2021) have discussed the design process of tangible storytelling. Their main contribution, in addition to design ideas, was a visual typology for narrative artifacts that connects concepts of tangible interaction and narratology. The goal of this typology is to help aspiring designers develop captivating stories that transcend screens and take place in the real world, using actual people and physical objects. The work responds to the need to showcase the distinctive qualities of tangible storytelling by underlining the significance of interacting with physical objects in a physical, embodied setting. Harley et al. (2016) have synthesized the tangible narrative design space into a preliminary framework, offering insights for designers who aim to create new tangible narratives and mapping out possible directions for future work. Their work emphasizes that diegetic objects, existing in both the story world and the user's physical space, hold promise for the future of tangible narratives, potentially offering an alternative to user interaction outside the story world. They also pinpoint the importance of narrative choices, both implicit and explicit, in shaping the user's relationship with the story world.

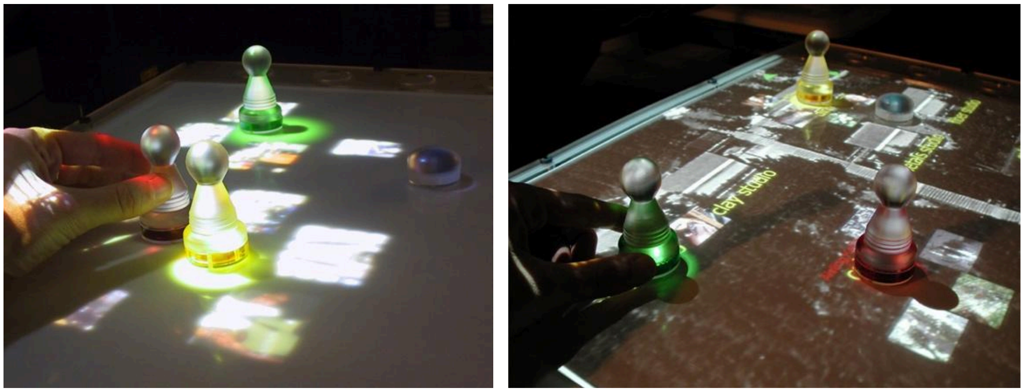

Figure 8: *Tangible Viewpoints (Mazalek et al., 2002) (left) and Tangible Spatial Narratives (Mazalek & Davenport, 2003) (right) used interactive pawns and other tangible objects on a tabletop surface with top-down projection to navigate multi-viewpoint and spatial interactive stories. [ALT TEXT: The left-hand photo shows a user grasping a pawn on an interactive tabletop display. There are also two other pawns and a small dome-shaped tool on the table. All three pawns are surrounded by thumbnails representing story clips. The right-hand photo shows a user grasping a pawn on an interactive tabletop display which shows a map of a story space. Two other pawns and a dome-shaped tool are positioned in different locations on the table. Thumbnails representing story clips surround the pawns at each location.]*

4.5 Arts and Visualization

TEI offers new opportunities for creating innovative interactive art and visualizations, which has inspired many researchers and designers. For example, the AR sandbox (Dewitz et al., 2018) is an example of TEI for creating music while users interact with and reside in it. It provides three different interaction concepts. First, users can interact with kinetic sand, like playing in a playground sandbox, which results in changes in the particle flow and triggers diverse sounds and music patterns. Second, a user controls AR content and settings from the on-body menu which is projected onto their left hand if the palm is facing upwards and thumb spread away, allowing them swipe through a list of options that control the system's essential functionalities, such as adding sound points. Third, the users can provide gestural input, by pointing a finger at specific areas of the system, to select a specific sound point. Based on a similar approach, Beckhaus et al. (2008) introduced GranulatSynthese, an interactive system based on granules distributed over a tabletop surface. On top of the surface, rear-projected visuals are displayed while dynamically selected sound samples are selected. The tangible surface is explored with the hands, intuitively shaping the sand into both hills and open space. The shape, location, and size of cleared areas trigger the system to generate audio-visuals.

Tomás (2016) delved into contextualizing the notion of *performative materiality* within the framework of tangible musical interfaces. Within this effort, the author presented Tangible Scores, a hybrid digital instrument and score deployed on engraved wooden panels. Users could interact with Tangible Scores by touching and or swiping their fingers on the surface, producing aural cues that were a composition of pre-analyzed sounds. These sounds were dynamically produced by taking into account the characteristics of the performed gestures, such as acceleration or duration. Another example is Tangible Landscapes (B. Bongers, 2020) which involved physical objects, sensors, and audiovisual components to facilitate the embodiment of remote scenes. The initial digital landscape was transformed into a new hybrid one by combining physical objects with technology, leading to diverse individual perceptions. Tangible Landscapes served to encourage social interaction, generate narratives and experiences that can be either personal or communal, and promote the appreciation of nature by inspiring contemplation on the relationship between technology and nature.

Murmur (Rydarowski et al., 2008) was an interactive installation that responds to sounds from its environment using embedded microphones. The installation featured a reactive surface made up of hinged paper pieces in front of fans. When it sensed any sonic input from the surroundings, including intentional sounds made by users, the installation activated its fans in a specific sequence. The movement of the fans created wind pressure that pushed the paper pieces, generating dynamic patterns that reflected the sonic characteristics of the environment.

As a final example, "The World as Your Palette" (Ryokai et al., 2005) aimed to empower artists to create visual art projects using elements such as color, texture, and dynamic patterns extracted directly from their personal objects and surroundings. The main tool for realizing this endeavor was the I/O Brush (Ryokai et al., 2004) which resembled a traditional paintbrush and employed a video camera, lights, and touch sensors. Beyond the traditional drawing canvas, this brush could capture the colors, textures, and movements of any surface it interacted with. On a digital canvas, artists could express themselves using this unique 'ink' they had collected from their immediate environment.

5. Conclusions

This chapter provided an overview of Tangible and Embodied Interaction, a field of Computer Science that engages users in the interplay between the physical and digital worlds through the manipulation of physical objects and devices based on the notion of natural human-computer interaction. The grassroots and the conceptualization of TEI was established in the late 1990s, when Ishii and Ullmer (1997) talked about “Tangible Bits” as the idea of coupling digital information with physical objects and surfaces at either the center or the periphery of human attention. As the field has evolved, there has also been an increased emphasis on embodied interaction, which often refers to interactive systems in which bodies move in space.

As discussed in Section 2.4, the field of TEI is part of a broad paradigm shift in HCI that places an increasing emphasis on the concept of embodiment. This also encompasses other fields within HCI, such as wearable computing, augmented and mixed reality (AR or MR), and ubiquitous and context-aware computing. A fundamental difference between TEI and wearable computing is that TEI typically does not take place on the human body but most often in a technology-augmented environment. Like TEI, AR and MR prioritize natural interaction with physical or virtual objects as a primary means of human interaction with technology. However, AR and MR focus primarily on incorporating visual representations into real-space and on connecting them to real objects; they typically do not involve the embedding of sensing, display, and actuation technologies into physical objects and surfaces, as is common in TEI. The area of ubiquitous and context-aware computing overlaps with TEI in its goal of incorporating computing technologies into everyday physical environments. However, research in this area places significant emphasis on having the system detect a user’s intention and act intelligently on their behalf given the context. In contrast, TEI tends to focus more on how users directly communicate their intent to a system through physical interactions, and how these interactions translate into changes in a system’s physical and digital representations.

The chapter discussed the foundations of TEI, unraveling pertinent interaction concepts such as Gibson’s (1979) idea of “affordance”, Norman’s (1991, 2008) “signifiers” and “cognitive artifacts”, Schneiderman’s (1983) “direct manipulation”, and Ullmer and Ishii’s (2001) Model-Control-Representation intangible/tangible interaction model. The chapter also discussed the concept of “embodiment” and provided a brief review of key ideas from areas such as phenomenology and embodied cognition that have fueled the third and current paradigm of HCI research, which emphasizes the importance of human consciousness rooted in bodily experiences in relation to the physical and social world.

The chapter presented several TEI frameworks that can help researchers and designers in defining, evaluating, and creating tangible and embodied interactions, such as the use of image schemas and their metaphorical mappings to inform tangible interaction designs, and the categorization of user interactions as either pragmatic or epistemic as a means analyze how tangible systems support problem-solving. The choices for interactivity, different types of supporting technologies, as well as the design tools and methodologies used to develop them, were also investigated as important concepts for the practical design and implementation of TEI systems. In this regard, the chapter gave several examples for research topics and application domains, such as learning and education, discovery and problem-solving, health and well-being, communication and storytelling, and arts and visualization, providing substantial evidence that TEI is an appealing interaction paradigm with broad applicability.

Although there are many research efforts on TEI solutions and methods, their integration into daily routines and environments is still very limited. Nowadays, immersive and engaging experiences that establish a more natural and intuitive connection between users and technology are becoming increasingly prevalent. This is one of the most notable features of TEI. The Metaverse concept and the development of virtual worlds that blend with reality are currently in the spotlight, and TEI approaches offer the potential to better center these experiences into the real-world physical and social context. In support of this, it is expected that TEI approaches will advance significantly in the coming years. From a technical perspective, this advancement will include the use of a wider range of sensors and actuators capable of precisely capturing and responding to users' natural interactions. Coupled with the current evolution of AI technology, TEI-enabled systems will be better equipped to understand human behavior accurately, bringing us one step closer to the envisioned era of unified virtuality and reality. Moreover, TEI systems can offer new ways to support a human-AI partnership, by leveraging and expanding on the existing work that has used tangible and embodied interactions for sensemaking around large and complex datasets.

Other future directions of TEI include integrating haptic feedback for a better immersive experience. More haptic interaction advancements are anticipated as the hardware and haptic devices continuously improve, providing the opportunity for more sophisticated haptic feedback mechanisms within tangible interfaces. This can enhance the sense of touch, allowing users to better feel textures, resistance, or even virtual sensations.

Another important perspective to be considered as a future direction for TEI is environmental sustainability. To achieve this goal, new TEI hardware designs should be put in place to minimize energy consumption, utilize renewable and environment-friendly materials, and consider the environmental impact of their lifecycle.

Despite the forthcoming technological advancements, addressing ethical and privacy concerns becomes paramount as tangible interfaces become more pervasive. Future research in TEI should explore frameworks for responsible design, considering issues such as data security, user consent, and the potential societal impact of tangible interactive systems. Balancing innovation with ethical considerations will ensure that TEI technologies are developed and deployed responsibly.

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