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ORIGINAL ARTICLE

Intangibles wear materiality via material composition

Hyosun Kwon · Hwan Kim · Woohun Lee

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Abstract The importance of material is gradually increasing in human–computer interfaces (HCIs), especially in the design of physical objects that embody digital information. Because digital information is not comprised of physical material (Belenguer et al., in Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, ACM, New York, pp 205–212, 2012) that provides tactile feedback, advancements in HCI research involve combining physical matter with digital representations to embed materiality in immaterial beings. The emergence of new material and transmaterial (Brownell, in transmaterial: a catalog of materials that redefine our physical environment. Princeton Architectural Press, New York, 2005) indicates that material is increasingly becoming a priority in the interaction design field. We emphasize the importance of material in interaction design and discuss categories of material properties according to the characteristics of interactive systems. We divide the pre-existing materials of interaction design into three categories: tangible material, intangible material, and computational material. The relationship between tangible and computational materials has been profoundly discussed since the origin of the tangible user interface. However, intangible materials, such as air, light, and magnetism, are commonly disregarded as distinctive categorical materials in interaction design. In this paper, we argue the effectiveness of intangible materials when they are coupled with tangible and computational mediums and discuss the framework for material composition in interaction design. The concept of material composition suggests the modification of a previous perspective in interaction design, which considers that materials must have either physical or digital properties. The framework of material composition proposes various configuration dimensions that correspond to the quality of the materials used. Therefore, we manifest the framework using Inflated Roly-Poly, which is a previously developed interactive artifact, to determine the success of the reconcilement among the constituent materials and to describe the potential for investigating and resolving further implementation issues.

Keywords Material · Materiality · Material composition · Interaction design · Transmaterial · Physical interaction · Embodiment

H. Kwon (✉) · H. Kim · W. Lee
Department of Industrial Design, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
e-mail: hyosun.kwon86@gmail.com

1 Introduction

> Phenomena exist in the material world.
> Material makes thoughts tangible.
> Materials manifest the world. – Viray [52]

Since the creation of the material world, materials have been a fundamental substance of the phenomenological representation of nature through which human beings perceive the ontology of the world (Fig. 1a). Materials manifest the world. However, the advent of digital technology has converted a vast amount of routine physical information into visual and auditory dematerialized forms—"from atoms to bits" [42]. Metaphorical icons and graphical buttons on a screen govern the interaction process in the digital domain (Fig. 1b). Currently, we belong simultaneously to a *physical world* that is represented by tangible materials and a *digital world* that embodies digital computation (Fig. 1c) via user interfaces, which increasingly blur the boundary between computation and materials [50].

Consequently, human perceptions of the world have been adapted to new materials that compromise both realms. Thus, different representational forms provided different views of the world and knowledge of everyday life (Ong [44], Goody [15]). Although the vast potential of computers suggests endless possibilities in the human–computer interface (HCI) field (Vallgarda and Sokoler [60]), it creates an imbalance in the human sensory apparatus. Flat and rigid computer screens display highly vivid superficial objects; however, they lack the haptic sense of texture, temperature, and weight—*materiality*. Furthermore, metaphorical graphical user interfaces (GUIs), which are manipulated by pressure on a keyboard and mouse or a touch screen, provide minimal rich sensory feedback compared with their physical equivalents. Kortum [29] aimed to introduce various non-traditional interfaces that address numerous human sensory apparatuses, other than the GUI, that are based on design guidelines from commonly used interfaces (e.g., speech user interfaces) to interfaces infrequently accessed by users (e.g., taste interfaces) [29]. Substantial efforts have been made in the tangible user interaction (TUI) field (e.g., 9, 48, 56, 57) and organic user interface (OUI) field (e.g., 18) to realize the full potential of the tangibility of routine matter via computation. The seamless blending of physical and digital objects has modified the exploration of the materiality of matter and has conveyed digital information from the computer system to the physical realm. Physical computing, for example, awakens static objects that are motionlessly situated in space to actively participate in interaction and communication with users [37]. Consequently, inactive objects are being converted into new materials and transmaterials [47] that embody transformable features within a given context. Figure 2 illustrates some examples of transmaterials, in which the property of one material is transmitted to another material to create a composite of a design material. Such materials deliver extraordinary experiences regarding both aesthetic performance and utilitarian functionality.

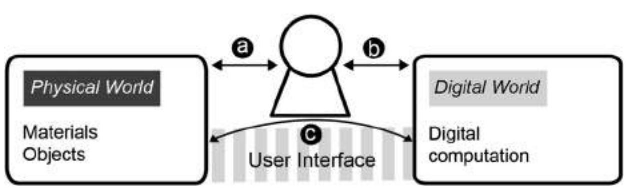


Fig. 1 Types of interactions that occur between the user and the physical and digital world

The appropriate coupling of material attributes evokes unique properties and qualities of new materials that could lead to innovative interaction techniques. We introduce the term *material composition* to discuss the methods and effects of entangling physical and digital materials within the context of interaction design. The material composition approach is concerned with not only reconciling the ontological distinction between digital and physical materials but also a more precise focus on material attributes. We consider the term *composition* in a macroscopic sense that does not address the physical or chemical reactions between matters, as in material science, but instead addresses the interactive and responsive enhancements between the materials. A composite material is a combination of at least two materials that are combined to create a new material composition with enhanced performance attributes, which surpass the individual performance of each material or the sum of the individual performances [49]. Materiality creates a user interface that produces a more complete system, which enhances its utilitarian value and/or its hedonic value.

Rather than pursue interaction methods for bridging the digital and physical worlds with a dichotomous viewpoint, we advocate "trichotomy" as a way to perceive a world that is mediated by interactive systems. We distinguish the physical realm with two different categorical materials, as illustrated in Fig. 3. We argue that the user interface occurs through the process of determining how *tangible, intangible, and computational materials* are integrated to form an innovative interaction technique and to derive an

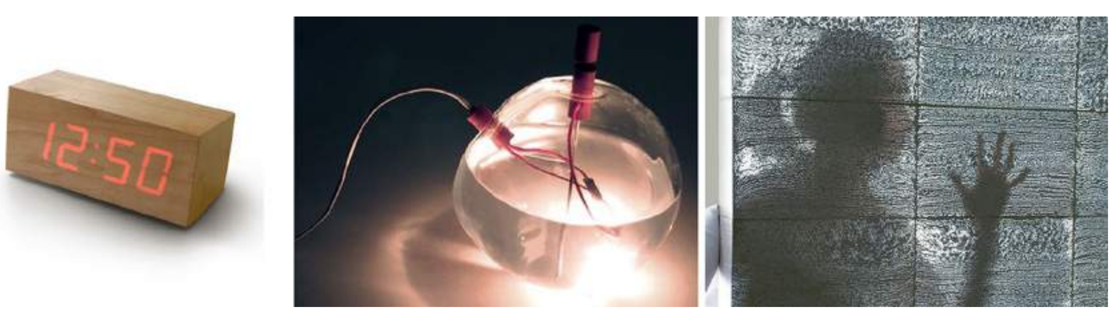


Fig. 2 *Left* wood clock—alarm clock made of maple wood that displays time with a light-emitting diode (LED) display; this clock was designed by Kouji Iwasaki [66]. *Middle* glass lamp with a water-submerged light bulb at its center; when a thin silver rod is slid into the water through a silicon gasket, the lamp turns on [63]. *Right* light-transmitting concrete developed by Áron Losonczi [34]

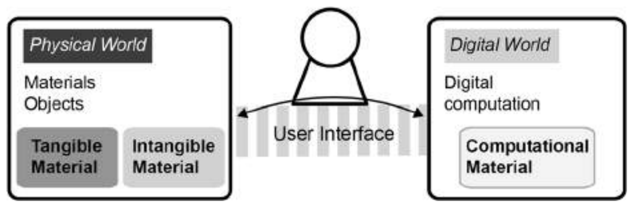


Fig. 3 Interaction in material composition: tangible and intangible materials form the physical world, which are linked to computational material through a user interface

aesthetical experience. In addition to tangible objects, we introduce the term *intangible material (air, magnetism, light, and sound)* as another category of material that comprises our physical world. The existence of intangible material is unaccountable in daily life and in the field of HCI. We introduce intangible material as an important factor that catalyzes material interaction. The theoretical framework of material composition will be based on previous research achieved in the field of HCI. We apply the composition framework to our previous design case of *Inflated Roly-Poly* [30], which is a playful tangible interactive media. The case illustrates how the intangible medium is entangled with other physical and digital components to mutually enhance the material qualities. We also examine how an embodied materiality appeals and contributes to interaction by conducting an experience workshop with 15 graduate and undergraduate students. The open-ended discussion culminating with a workshop helps to reveal the effectiveness of materiality in interaction design. We attempt to construct a framework of material composition that may develop a broadened perspective for shaping interactions in a more sensuous manner. Materiality will be treated as one of the design attributes that contribute to the design of aesthetic material interactions [35].

2 Terminology

2.1 Composition

Composition generally denotes the combination of parts or elements to form a whole. Although various new materials have been developed in the field of material science by composing properties of different materials, the practice of designing material interaction involves the combination of existing materials to create a meaningful whole [64], which leads to improved performance. For example, Vallgårda and Redström [59] introduced the notion of a computational composite for treating the computer as a constituent of material composition. Vallgårda and Sokoler [60] argued that composite materials represent an enhancement of some of the properties of their constituents and a suppression of other properties of their constituents. The idea supports our approach in terms of the perception that material composition produces a range of augmented effects in interaction design. Wiberg and Robles [65] addressed the notion of "computational compositions," with regard to the aesthetics of interaction design, by introducing the relational language, "texture," and analyzing digital-physical compositions through critiques of the ontological distinction between atoms and bits. Our approach to composition differs in that we acknowledge the ontological distinction of the physical and digital domains. To achieve a novel interaction through reconciling the digital and the physical worlds, we employ the substrates in each domain as raw materials to apply various methods of composition.

2.2 Tangible material

The word tangible is defined as a type of property that can be perceived by touch [45]. Tactility, weight, and form are the features that comprise the tangibility of a material. A tangible material concerns real objects that are physically logical, and thus, their existence is easily recognized by the human senses under natural conditions. Manzini employed the term "mute objects" to describe tangible materials, such as woods, clay, fabric, water, and glass, which we encounter in everyday life. Naturally, the existence of tangible materials can only be expressed through a firm locatedness in our surroundings over time. They have limited ability to change their features—size, texture, or weight—in real time. Their explicitly rendered characteristics offer affordances when placed in specific usage situations. When an object presents itself in tangible form in a user's hand, interaction techniques can be easily learned. The materiality conveys the way the object is perceived and the experience the object enables [37]. Topological properties, such as orientation, form, volume, texture, viscosity, and spatiality [48], provide a distinct physicality of materials.

As tangible materials participate in HCIs, they require computation to interact dynamically with the user or environment. The TUI causes physical materials to shift their attributes from a rigid and stable quality to a flexible and changeable quality; thus, the materials seamlessly couple with digital representations, such as video projections or sound. As a result, the material becomes the base of the immaterial object, which we subsequently define as computational material. However, we do not consider passive input devices (a keyboard or mouse) or system hardware (a central processing unit (CPU) board or sensor) as tangible materials in this paper. For example, the material used to design a typical keyboard has no relevance to its interface of the action of typing. Using such devices, interaction is often learned through words and trials. The devices' materiality rarely defines the interactivity.

2.3 Intangible material

In this paper, we introduce intangible materials—air, magnetism, light, smoke, and sound—as substances that reside within natural settings but are often rejected due to their invisible or untouchable properties. We position these intangible materials at the center of our interaction model as mediums that enhance tangible properties of materials and augment physical interaction. The term *medium* is defined in two ways: one definition entails a substance through which something acts or is conveyed, and the other definition entails a middle quality, state, or size [45]. In this study, we commingle the two definitions into the concept of the intangible material. Although they are rarely naturally visualized due to the physical characteristic of raw materials, intangible substances can become tangible, such as physical objects, under certain conditions and settings (e.g., air contained in a rubber tube). Thus, in the framework of material composition, an intangible material can be considered as a substance that is capable of behaving in one way or another through its middle quality. Intangible materials possess such properties as editability, volatility, and transparency. Thus, when intangible materials are enclosed by tangible materials and embed digital information in the interactive system that materializes invisible mediums, they provide ample sensory feedback through the interaction process.

In the interaction model of the TUI, the intangible medium has been considered as a digital representation that includes video projection and sound representation, through interaction output [56]. Conversely, in our framework of material composition, an intangible material surpasses the representation tool and is involved in the interaction for both input and output. Hence, we consider the digital representation of the TUI—audio/visual representation—from two different viewpoints. One is the viewpoint that the sound feedback or projection image is employed only as digital information; we classify it as immaterial or computational material because it is the alternative representation of digital bits and bytes. In this case, the digitized sound and images are responsive elements of interaction that only verify a user's physical input. The other viewpoint is that when the sound, projection image, or any light source shapes a certain materiality, it enhances interactivity as a texture that increases the relationship between the materials [e.g., [49]] and re-designs its composition along with other materials. In these instances, a digital light source or sound is regarded as an intangible material.

2.4 Computational material

> A child is playing with a ball – he tosses it against a wall, the ball executes a trajectory, bounces back, (…) The cycle is repeated several times, then the screen goes blank and two words appear – "GAME OVER" – the child has finished and exits from the immaterial environment (…) [37].

While living in a (macroscopically) dual physical-digital world, we typically encounter situations in which the physicality of a material on a screen resembles a physical and real environment. As Löwgren and Stolterman [36] described a computer as a material without properties, we regard the computer as immaterial. In terms of computational interaction, *immaterial* or *non-material* refers to bits and bytes or any digital information that begins with a calculation process of zeros and ones. In this paper, we use such terms as computational material, immaterial, digital information, and digital material, including system hardware, interchangeably to describe materials that lack tangible properties. We consider system hardware and sensors digital material because their physical characteristics only protect the computing process. Although digital information is often realized through displays and sounds that utilize symbolic and metaphorical forms, as in a GUI, it is simply a dematerialized entity. As suggested by Manzini, we also regard digital information as immaterial and belonging to a *third* dimension of existence [37]. However, we accept the notion that digital information has the ability to affect other materials and is perceivable through the human sensory apparatus [59] when clothed with tangibility and physicality via tangible materials or intangible mediums. Computational material has been widely utilized as a design material in contemporary HCI applications for the utilitarian value of functionality but has been merely revealed in a physical or tangible manner. Sundström et al. [55] aimed to utilize the dynamic properties of digital materials as design sources for networking systems and inspirational bits. They designed several prototypes to explore the feasibility of technology as a design material with functional potential to induce engaging experience rather than as a design material with incorporative potential and other physical entities. However, the approach taken in this study is to physically visualize the tangible quality of digital material in the material composition. Designing digital network systems in a tangible manner is a potential goal based on our approach to the "inspirational bits."

3 Material composition in interaction design

We argue that the role of material in interaction design falls between serving technical and product functionality for

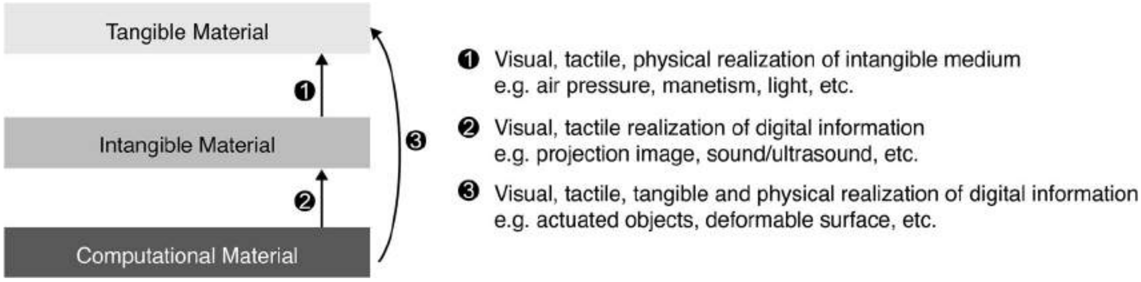


Fig. 4 Multi-sensory realization occurs within the composition of materials

utilitarian value and the aesthetic interaction that enhances the hedonic value. Through the lens of materials, we can consider design as a process of creating meaning with proper materials based on exploratory practice [25]. Therefore, understanding the methods and effects of material use has become crucial to the design field. Figure 4 illustrates how one material can enhance another material through the channel of the human sensory apparatus. Each category of material manifests the other categories of materials through various senses.

For example, the colloidal display (Fig. 5), which was developed by scientists at the University of Tokyo, Carnegie Mellon University, and the University of Tsukuba, is a multi-layered colloidal transparent soap bubble display that has an ultra-thin and flexible quality. A scale of ultrasonic waves that alter transparency and surface states controls the colloidal screen. The display clearly illustrates the exploration of novel experiences via material composition. Tangible colloidal liquid and intangible ultrasonic sound and light are commingled to produce a display with enhanced interactivity. The display consists of a multi-sensory realization of materiality, as illustrated in Fig. 4.

The goal of material composition in interaction design is to create an entire experience from several iterations of input and output via the integration of two or more materials. Numerous research projects exist that depict the blending of representations in physical and digital domains into a single system. This section reviews some related works of interaction design from the perspective of material composition to explain our proposed framework, which we subsequently introduce. The composition is identified by each category of materials that are primarily used to construct the entire system.

3.1 Material composition incorporating tangible materials

Numerous projects in the boundary of the TUI framework, which were led by the MIT Media Lab, made a progressive shift from the GUI paradigm. Pixelated graphical representations are embedded on tangible materials. The focal

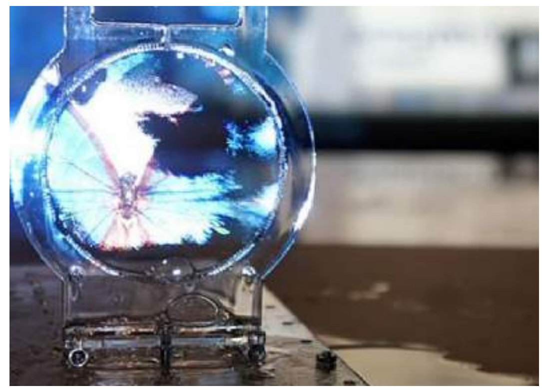


Fig. 5 The colloidal display constructed from a mixture of two colloidal liquids that form a membrane screen, which allows light to pass through it, and displays the color of the light on its surface [12]

consideration of material composition in a TUI is the representation technique of the physical manifestation of computation. An example of early tangible interfaces is the URP, which employs a physical-scale building model coupled with the digital representation of urban simulations of shadow, wind, light reflection, and other properties via video projection [57]. The purpose of the project was to transport the tangible controllers onto the surface of the workbench and merge them with digital representation. Other related studies of discrete tangibles on a two-dimensional tabletop surface utilized the reacTIVision toolkit, which made use of the augmentation of tangible objects via digital information located underneath the surface [e.g., 24]. However, the materiality of the tangible object on the tabletop engages in minimal interaction; instead, the metaphorical and topological forms of the object are merely involved as mediators of the interaction process. It is inconclusive whether the materials are composed to create the wholeness of the system when their existences are used to track their orientation and location. Transformable and deformable surfaces, such as lumen by Poupyrev et al. [47] and Recompose by Blackshaw et al. [6], represent transformations of tangible materials that are firmly synchronized with an underlying computation that detects gesture inputs, which actually enhances interactivity through its real-time response. Some tangible interaction studies, including those mentioned previously, partially embedded light (image/video projection), which we previously defined as an intangible medium, as one of their output sources. Kinetic surfaces [e.g., 26, 32] and actuated tangibles often utilize the physical qualities and topological orientations of the materials. The invisible quality of digital computation is enhanced by the materiality (soft and flexible property of spandex in [26]) and physicality (gravitational force due to the weight of pins in [32]) of the components. Stronger bonding of tangible and computational materials has been explored for transitive materials [10]. Programmable smart materials and effortless computing seamlessly coupled with an artifact's composition to generate tangible aesthetic interactions [9].

The limited ability of a TUI to change the status of the physical properties [22] prompted us to seek a method in which a modification of one property can be reflected in the modification of another property via action-and-reaction, which occurs between the comprised materials in an interactive composite. For material interactions incorporating tangible or physical materials, the focus is the precise methods that lead physicality to tactual and embodied human practices [16].

3.2 Material composition incorporating intangible material

Intangible materials are widely used in the interaction design field. Some of the materials in this category, such as air and magnetism, are unrecognizable in natural settings. However, their presence becomes ascertainable when they are composed in an interactive system with materials from other categories. Strong and Gaver [54] designed simple network devices using omnipresent intangible materials, such as air and scent, which invite implicit, expressive, and poetic communication. The soap bubble user interface [13] is a material-centered interaction design that utilizes thin and flexible surfaces. Air or smoke, which is initially intangible, becomes graspable when it is composed of tangible soap liquid. Immaterial computation beneath the system allows the interaction to be an innovative and engaging experience with familiar materials. Air, or pneumatic, becomes tangible when entangled with tangible materials [e.g., 27]. Both ZeroN [31] and Blob Manipulation [61] utilize magnetism in interaction. The invisible but force-generating characteristic of magnetism produces an unpredicted haptic sense via material composition. A light source from a projection image on a tangible and deformable surface augments the tangible materials, and their enhanced materiality improves their functionality [e.g., 46]. Light also reinforces the aesthetic quality of tangible materials. IceHotel X [65] is a design that incorporates a composition of digital display (light) and frozen water to increase the beauty of texture. In the case of IceHotel X, Wiberg regarded light as a computation. We rearticulate this finding as follows: in our framework, light is an intangible material, whereas computation is immaterial. However, in the case of *light*, we are occasionally confronted with a situation in which the use of light only slightly enhances the materiality (e.g., image projection is intended for display only); in such cases, we do not consider light as an intangible material.

3.3 Material composition incorporating computational materials

Digital information always functions as one of the constituents in the HCI. We regard calculation and computational processes of 1s and 0s, which occur in hardware and software systems, as immaterial because they do not embody any specific forms that are discernible by the human senses. Accordingly, displays constitute confusing matter that is difficult to thoroughly categorize in the framework. For example, although the 3D display in the Holodesk, which was developed by Microsoft Research (2011), can be directly manipulated by hand, it is a 3D representation of a GUI using 2D displays. We also categorize the projection images or icons as immaterial if they have no relation to the back surface or object in terms of enhancing the materiality. Although we categorize the laser of sticky light [8] as an intangible material, the light employed in lumen [47] is considered a computational material. The laser spot in sticky light converts the fluidity of the laser into a manipulatable substance that exhibits *sticky* materiality. However, the light in lumen is another simple indication source, such as a deformable surface, and there is a minimal blending effect between the light and surface.

4 Interaction framework for material composition

We have discussed interaction design while focusing on the valuation of material composition. *Composition* is broadly used within different areas. In material science and related technology disciplines, the term often refers to the combination of different constituents to form a new structure of material that produces better performance. Communities of music and literature also use the term *composition* in relation to the structure of a music or art piece that is composed of harmonized elements. In this section, we introduce our framework of the macroscopic composition of materials. We classify the material compositions with four distinctive categories, which are visibly represented and directly identifiable by the human senses. In the framework, input and output are not defined by one material category because certain entangled materials can behave symmetrically [43] as input and/or output, according to the context.

We establish the dimensional distinction of composition according to the number of constituent material categories, as shown in Fig. 6. We demonstrate the characteristics of each dimension of composition with related research.

4.1 2-State coupling

Two different states of material categories are coupled in this dimension. In our composition framework, there are two dimensions that correspond to two-state coupling.

4.1.1 Tangible computational composition

The first dimension that we propose in our framework is the composition between tangible and computational materials (Fig. 6(1)). Relevant examples to illustrate which constituents are coupled with which counterparts are displayed in Table 1. Examples in this category partially involve light or a projection image as an output. As light and projection images are subordinate factors of compositions or an extension of system hardware, such as displays, they are considered extended computational material. Each of the experiments constructed with tangible computational composition employs different approaches to materiality. Embodied tokens are the physical tags of digital information. The tokens simultaneously function as the manipulation tools and physical representations. The immaterial properties of the computation are separately rendered on the tangible materials. Examples of a kinetic/actuated deformable surface consider the position or orientation of the material. Wooden Mirror [51] and shade pixel [26] use natural shade—which partially involves the immaterial—produced by the status of the materials to create an experience of a meaningful whole [49]. Some of the studies conducted under the theme of direct touch interfaces focus on the methods of delivering haptic senses via various physical surfaces that are activated by obscured computation.

4.1.2 Intangible computational composition

Another category in the two-state coupling dimension includes the compositions of intangible and computational materials (Fig. 6(3)). The studies are grouped in subcategories according to the interaction features expressed by the composition. Haptic feedback and bare-handed interactions are the prevailing attributes revealed by the compositions (Table 2). TeslaTouch by Bau et al. [2] utilizes a touch screen system and employs electro-vibration to provide texture on graphics via haptic feedback. This device is distinguished from other touch screen devices that are incapable of generating tactile feedback or materiality of the objects within the context. Humantenna [11] performs bare-handed and real-time interactions with whole-body interactions. The research shows the successive use of electromagnetic noise (intangible medium), which facilitates ubiquitous computing. The device is also distinguished from other bare-handed gestural interactions that utilize a webcam and markers or gloves to detect the hand gestures. SixthSense [40] is a remarkable project that has endeavored to augment our physical world with digital information. Because the primary role of digital information in the system involves detecting the markers and projecting GUIs onto everyday objects, we regard SixthSense as a single computation (Fig. 6(4)) in which only the immaterial constructs the system with the user.

4.2 3-State coupling

The interactive composites in this dimension demonstrate the artifacts of three different materials that are entangled seamlessly.

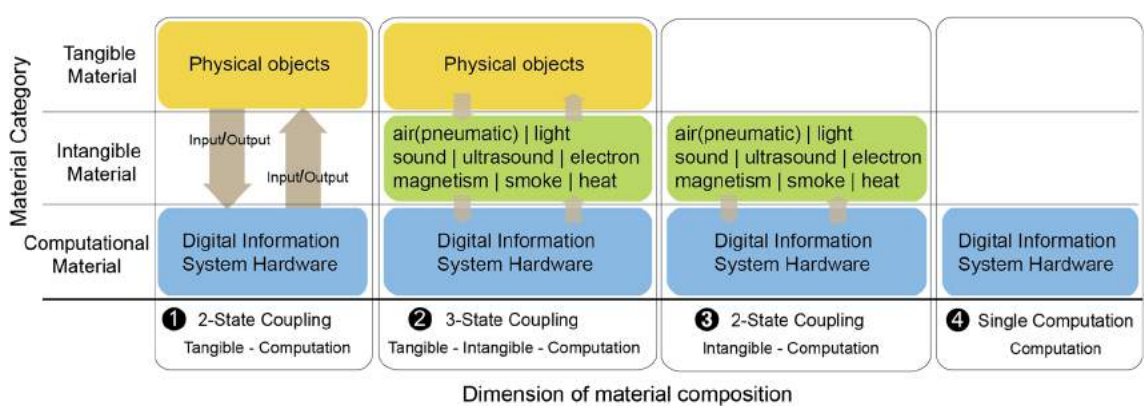
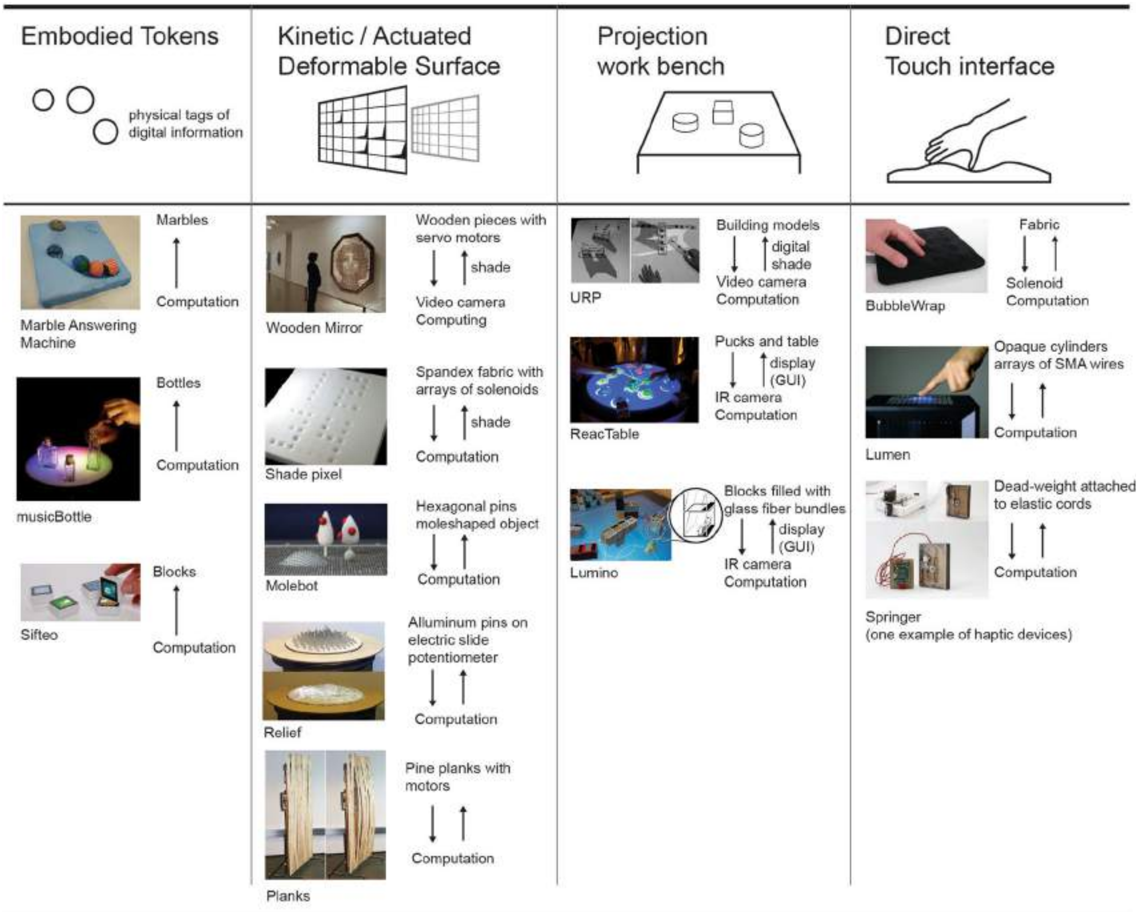


Fig. 6 Framework of material composition classified by the dimension of composition

Table 1 List of examples for the dimension of tangible computational composition. Examples are categorized by the external attributes possessed by the composites (Marble Answering Machine [5], musicBottle [21], Sifteo [53]), Wooden Mirror [51], Shade pixel [26], Molebot [32], Relief [33], Planks [58], URP [57], reacTable [24], Lumino [3], BubbleWrap [1], Lumen [47], Springer [41])



4.2.1 *Tangible–intangible computation composition*

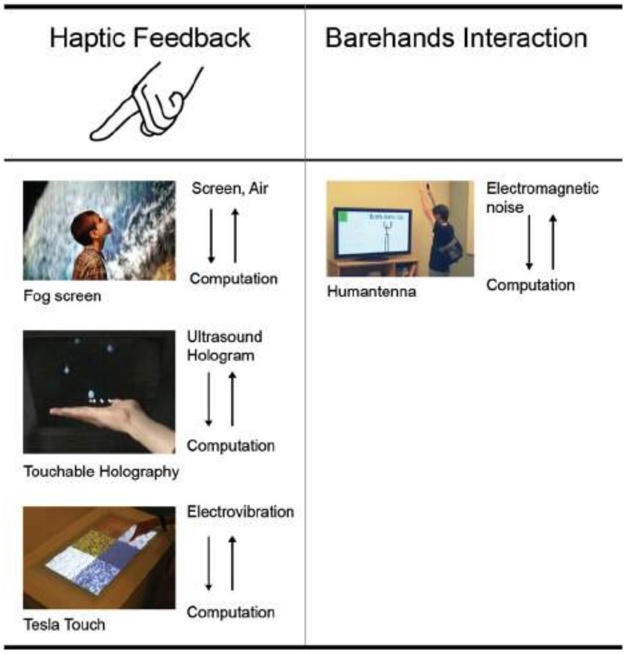
In this categorical dimension, we subdivide the examples of studies by the types of intangible materials that primarily create the interaction style of the system. To establish subcategories in the dimension, we extract the most prevailing mediums of a HCI. We often employ magnetism, air (pneumatic), light, and sound in interaction design without denoting them as intangible materials or without perceiving their existence because their invisibility helps the mediums to integrate seamlessly into the entire system. For instance, the invisible qualities of magnetism exhibit extraordinary phenomena that rarely occur in the natural physical world, such as the levitation of a heavy metal object. In addition, digital information, which we defined as computational material, enhances the interactivity of both tangible and intangible constituents by digitally transforming physical properties in real time. A list of relevant examples is presented in Table 3.

Tower of Winds by Toyo Ito [23] is an interactive architecture that responds to wind speed and directions without human input. The facade, which is composed of lamps and neon rings, translates the ever-changing flow of air into dynamic and aesthetic light displays. The configuration of transparent facade, wind, light, and computation visualizes an entangled practice, which enables the intangibles to wear materiality.

5 Design case: inflated roly-poly

Air balloons and roly-poly toys are objects familiar to people of all generations. Neither object requires specific instructions to play. The materiality of the air balloon implies softness and lightness, as well as deformability and malleability. When we squeeze the balloon, tactile feedback varies according to the density of the air. The swaying motion derived by the form of the roly-poly affords bodily action, such as pushing or tapping. The heavy and curved bottom surface of the roly-poly transforms the exerted input into a kinetic motion. In this study, we utilize the

Table 2 List of examples in the dimension of intangible computation composition. The examples are categorized by interaction characteristics (Fog screen [14], Touchable Holography [19], Tesla Touch [2], Humantenna [11])



inherent materiality of air and the innate physicality of the roly-poly in interaction design by incorporating our previous design of Inflated Roly-Poly [30]. Inflated Roly-Poly is a new type of interactive media that simultaneously deploys the materiality and physicality of materials. The prototype was designed to encourage novel experience with enjoyable interaction techniques. We review the design of the prototype and reconstruct the meaning of the materials in the framework of material composition.

5.1 Material composition in inflated roly-poly

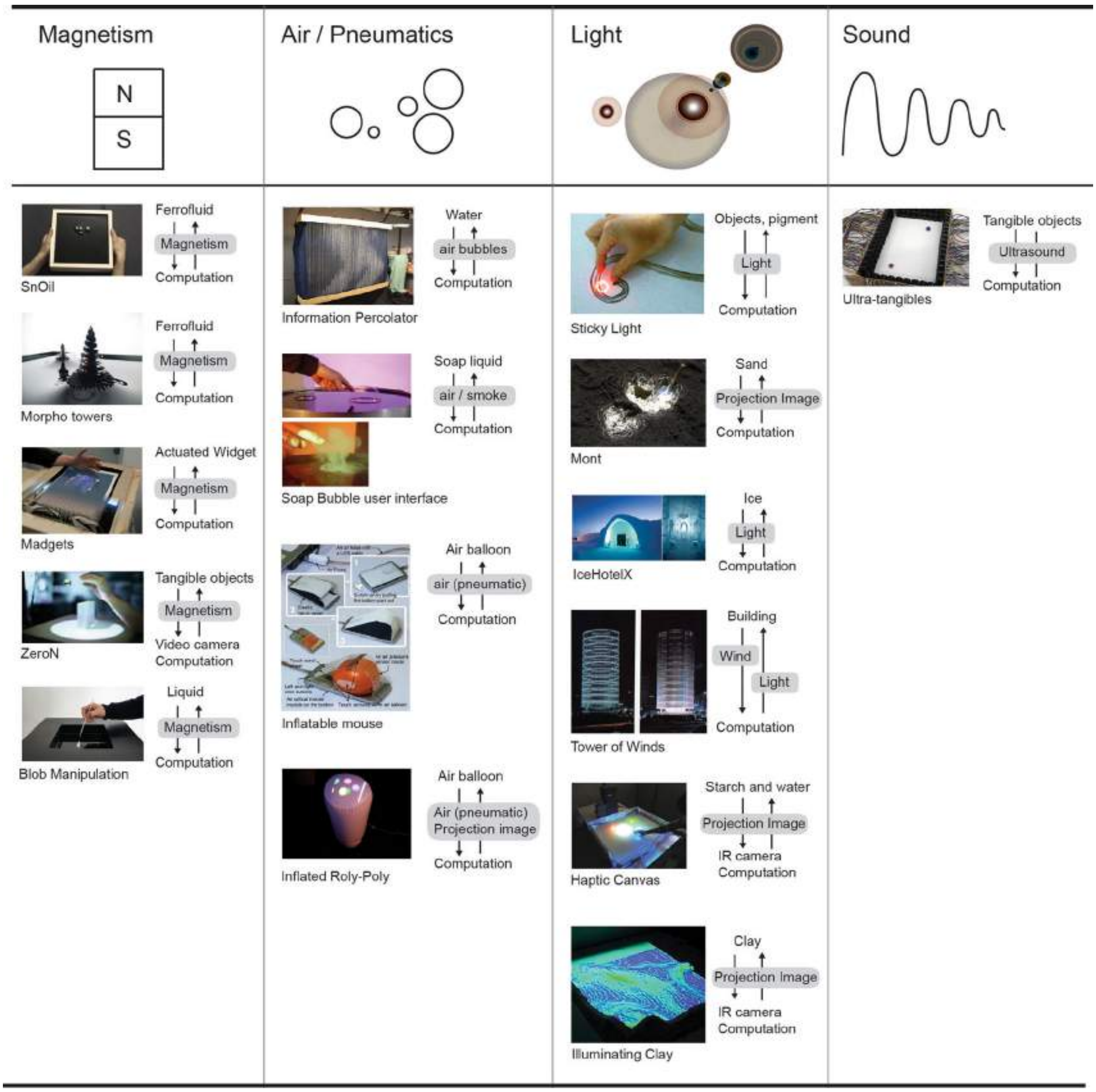
The exterior of the roly-poly is comprised of a basic construction with two parts: a white polyvinyl chloride (PVC) inflatable balloon mounted on a hemispherical bottom part composed of acrylonitrile butadiene styrene (ABS), as illustrated in Fig. 7a. The bottom edge of the inflatable balloon is attached to an acrylic ring with three screws, with heads facing down, and nine infrared (IR) LEDs facing an inflatable balloon. The screws fit into the holes on the bottom hemisphere.

The inflatable balloon functions as a deformable multi-touch screen by utilizing the back-projection technique. The hemispherical bottom part is comprised of an IR webcam, a pocket LED projector (Vivitek® Qumi) and a nine-degree-of-freedom (9-DOF) sensor stick (Figs. 7b, 8). In addition, an air pressure sensor (Motorola®, MPXH6115A6T1CT, 15–115 kPa) is embedded inside the balloon to make the screen pressure sensitive and touch sensitive. A 9-DOF sensor stick (SEN-10724 includes the ADXL345 accelerometer, the HMC5883 L magnetometer, and ITG-3200 gyro) is located on the bottom part to detect the spatial movement of the prototype. The sensor stick sends pitch, roll, and yaw data to the CPU via serial communication that allows the physicality of the prototype to be applied in the interaction process. Accordingly, a projected display shows the reaction of the prototype in real time as it senses physical inputs by the user (Figs. 9, 10).

The interactivity of Inflated Roly-Poly is closely linked with the materiality and physicality of the prototype. According to our material composition framework, the construction of Inflated Roly-Poly is based on three-state coupling in material composition, which is an interaction technique that incorporates the air-filling balloon as the intangible medium. It also comprises two-state coupling, without the utility of air, in which movement and orientation of the prototype become the only interaction sources (Fig. 11).

The dual modes of material coupling present in the prototype enable multimodal interactivity [29]. Air, which is originally an intangible medium, is the physical and literal focus of the design, as illustrated in Fig. 12. It closely links the tangible materials (PVC balloon and hemispherical roly-poly bottom) and computational materials (sensors and digital information) to form an aesthetical whole with unique interactivity. The PVC balloon contains air and provides tangibility. The firmness of the air transmits passive haptic feedback via the tangible skin of the balloon. Moreover, the invulnerable quality of the air-filled balloon conveys the affordance of physical input actions, which is radical compared with other digital artifacts. Accordingly, the physical attributes of Inflated Roly-Poly absorb the exertion inputs by changing the orientation and position of the body. The embodied computational materials convert the spatial movement of the prototype into interactive contents. The computational materials realize the existence of the air through alteration of its pneumatic status and visualize the tangibility of the air in digitized form (display and sound). The composition of the materials in Inflated Roly-Poly indicates the entanglement of three categories of materials, revealing that interactive composition surpasses the integration of digital and physical materials. The touch- and pressure-sensitive surfaces constructed on a heavy hemispherical bottom enable the tangible and physical realization of intangible materials and computational digital information. We argue that the computations in Inflated Roly-Poly enable not only flexible changes in the material expression but also controlled transitions between the composite material states [61].

Table 3 Examples of the dimension of tangible–intangible computation composition. Examples in this dimension are categorized by their relevance to the entailed material that performs the interactivity (SnOil [39], Morpho towers [28], Madgets [62]. ZeroN [31], Blob Manipulation [61], Information Percolator [17], Soap Bubble user interface [13], Inflatable mouse [27], Sticky Light [8], Mont [20], IceHotelX [50], Tower of Winds [23], Haptic Canvas [67], Illuminating Clay [46], Ultra-tangibles [38])



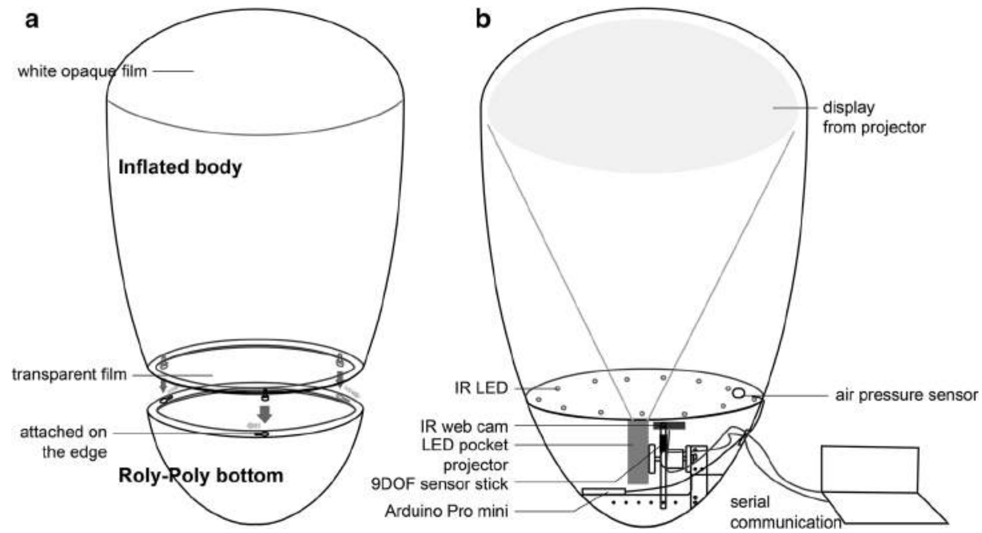
6 Experiencing materiality

As discussed previously, Inflated Roly-Poly is an interactive composite that comprises three different categories of materials, which exist in a physical, digital, and dual-faced world. We conducted a participatory design workshop with Inflated Roly-Poly to manifest the effectiveness of the material composition. We assigned participants predesigned interactive contents. The purpose of the workshop is to determine how people comprehend the idea of interactivity, which was induced by the physical movement of the prototype and the tangibility of the air-filled material. We assumed that the entangled practice of the material composition would present a unique experience and engagement. The topologically equivalent quality conveyed by Inflated Roly-Poly contrasts with experiences that people typically have with rigid touch screen devices, especially in terms of emotional engagement rather than functionality.

6.1 Participatory design workshop

The workshop was conducted with 15 students: six mechanical engineering graduate students, six industrial design graduate students, and three industrial design undergraduate students. The students were divided into five

Fig. 7 **a** External structure of Inflated Roly-Poly. **b** Internal structure with components [30]



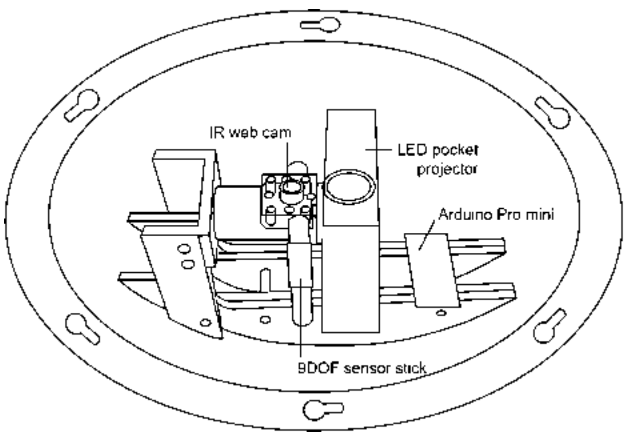


Fig. 8 Detailed view showing how the components are located inside the prototype

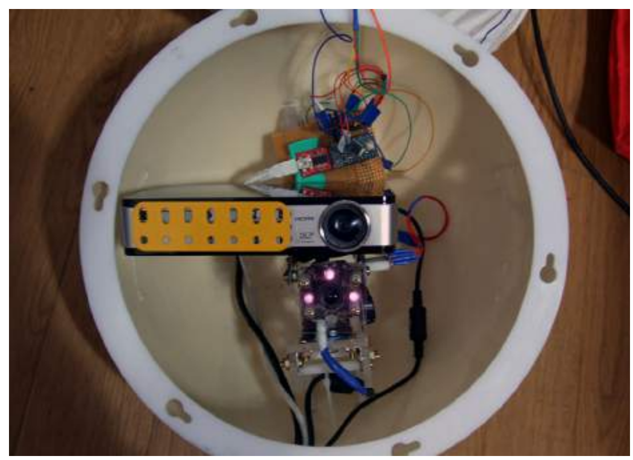


Fig. 10 Assembled view of the system components inside the *bottom* part of the prototype

Fig. 9 Exterior of the prototype assembled in one unit

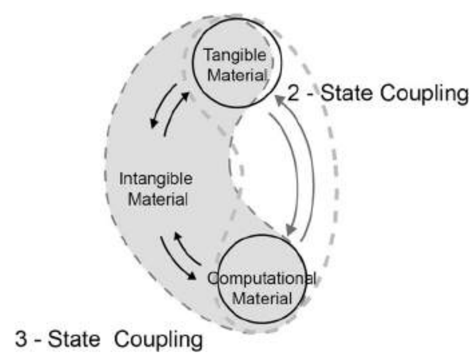


Fig. 11 Structure of material composition in Inflated Roly-Poly. It comprises two different dimensions of coupling in terms of interactivity

groups, with three students in each group. The average age of the participants, who were comprised of ten males and five females, was 24.87 (standard deviation (SD): 2.13). The workshop was held in one of the studios in the Department of Industrial Design building at KAIST. The duration of the workshop was approximately 45 min: each workshop session was recorded by video camera. There was a 10-min warm-up session to discuss the form factor of

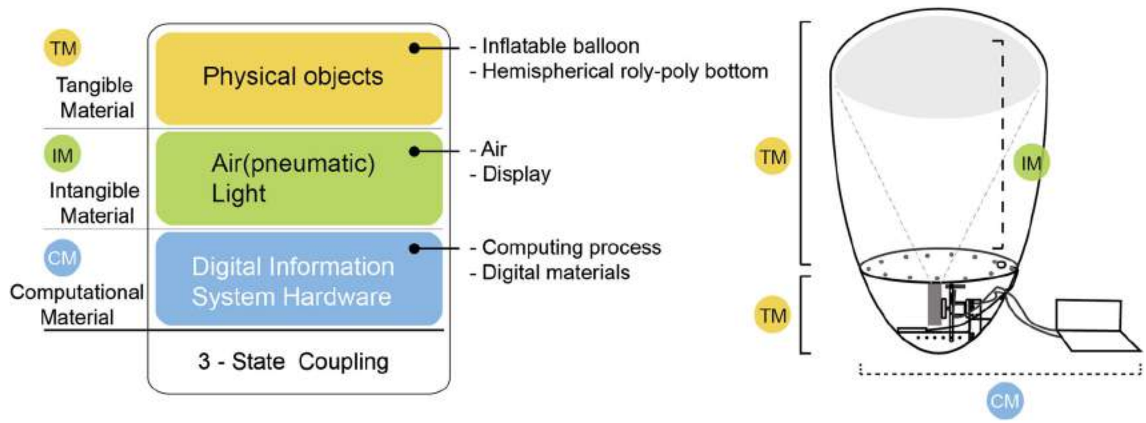


Fig. 12 Systematic layout illustrating the material composition in Inflated Roly-Poly

Fig. 13 *Left* participants examine Inflated Roly-Poly and discuss its uses. *Right* detailed view of the physical interaction applied on the inflated surface

the prototype, in which participants could guess what the prototype was and how it worked. Another 20 min of the session provides the participants an opportunity to touch and feel the materiality of the prototype with interactive content on the surface. During the session, a game application named Bubble Pop, which we developed, was demonstrated, and participants were given a chance to experience the application. After experiencing all contents of the prototype, we engaged the participants in an open-ended discussion in which they expressed their thoughts and feelings about the material and the physical interactivity. During the discussion, participants compared their experiences with Bubble Pop with a similar application on the iPad. The workshop concluded with an exploration of potential improvements and applications for Inflated Roly-Poly (Fig. 13).

At the beginning of the workshop, the prototype was located in the middle of the studio with the projector turned off. Most of the participants anticipated that the prototype was related to exertion sports or a children's toy; some of them thought that it was embedded with some type of light source and could interactively change color according to a swaying motion.

6.1.1 Application: Bubble Pop

The application we developed to fit inside Inflated Roly-Poly is named *Bubble Pop*, which encourages physical input as an interaction technique. The surface was designed for a touch-sensing display; thus, when participants poke or punch bubbles that are displayed on the screen, the bubbles disappear with popping graphics. In addition, the movement and tilting angle of the prototype is also applied on the screen, so that participants can search for the bubbles that have been spatially distributed in the virtual 3D space. When participants actually approached to play the game without being given any instructions, they gently touched the surface as they did with flat touch screens. After a short period, the participants applied poking and pinching gestures and soon familiarized themselves with the idea of interaction. We initially expected that the participants would aggressively handle the inflated body; however, in one group, they touched it smoothly and gently pressed on it with their fingers. One female participant responded as follows: “Air inside the balloon made me feel like the prototype is a soft and weak artifact, so I unconsciously poked lightly with my fingers.” In another group, the participants were competitively popped the bubbles, which motivated them to perform engaged actions such as tapping and punching. One participant made the following statement: “Since the air is non-breakable, it reminded me of a punching bag, so I treated it like one” (Fig. 14).

When the physical gestures were introduced, Inflated Roly-Poly responded by making spatial movements and displaying virtual space in which bubbles were located. Participants were initially amazed and confused when the display altered as the prototype tilted or rotated. They soon understood the concept of spatial interaction and began scanning the entire virtual space to find the bubbles. Participants explored the physicality of Inflated Roly-Poly while performing active bodily movements (Fig. 15). Participants in group 5 responded as follows: “It is very interesting that the surface displays so much broad space with its limited size.” Another person remarked as follows: “Yes, the entire display is a half-sphere where the roly-poly can cover, so it’s got hidden spaces.”

6.1.2 Other interactive practices

6.1.2.1 Map We projected an image of a street map onto the surface. Without being given any instructions, participants were allowed to examine the map using the physical interactions that they experienced in the Bubble Pop application. They pushed the prototype to induce a swaying motion and to determine whether the display also showed unrevealed locations, as in the previous application. When they were asked to zoom in on the map, some of the participants who preferred flat touch screen devices slid their fingers on the map; as they did performed this motion, they pinched and raised their fingers to zoom in and out on the touch screen. However, they acknowledged the property of the air-filled display and began to grab the display to view it more closely or firmly held the side of the inflated body to enlarge the surface and view the map in further detail.

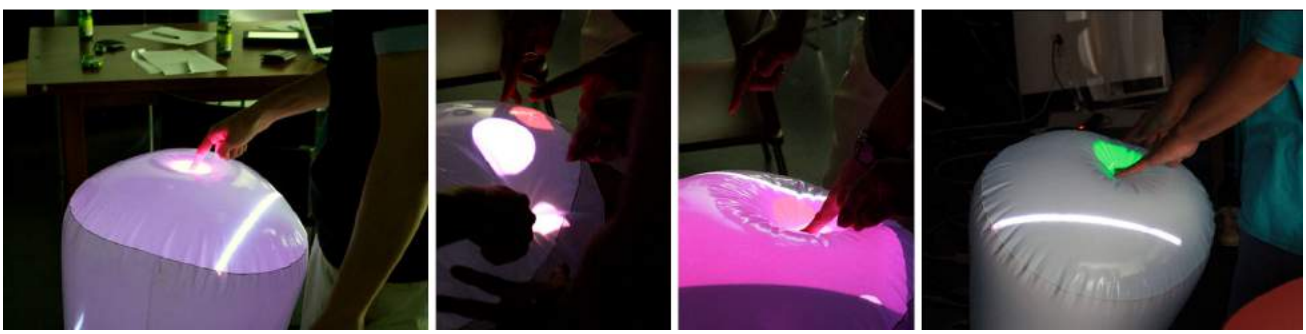


Fig. 14 Participants poked on the inflated screen and tried to burst the bubbles

Fig. 15 This sequence of photographs shows participants tilting the prototype to find hidden bubbles that were distributed throughout the virtual space

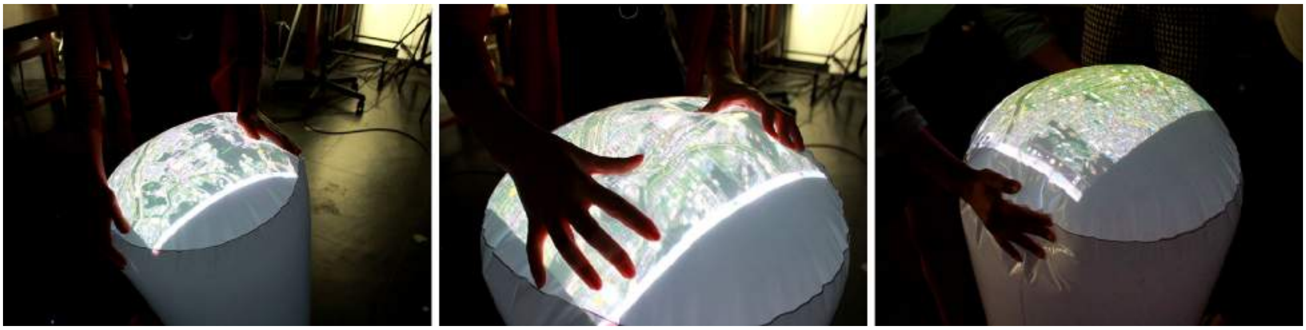


Fig. 16 *Left* navigating the map by tilting the prototype. *Middle* grabbing the actual screen to view the specific location precisely. *Right* grabbing the prototype on its side with two hands to zoom in the map

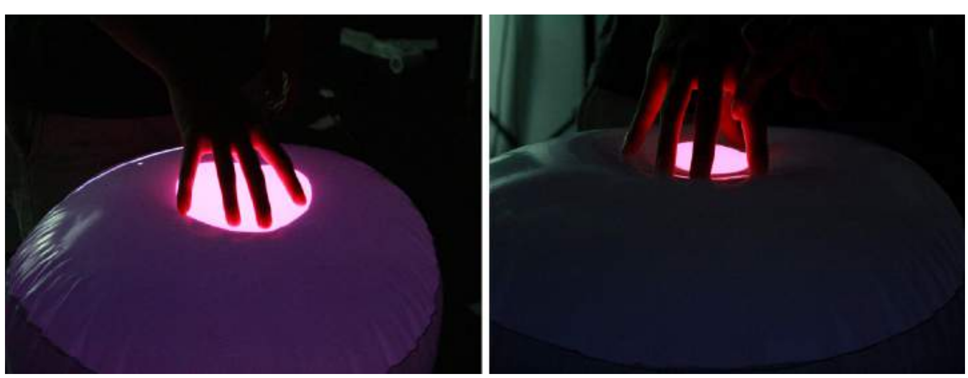
Fig. 17 Participants tried to resize the shape by squeezing the surrounding area

The map was programmed to zoom in when pressure was applied (Fig. 16).

6.1.2.2 Resizing a circle Because touch screen devices are widely used in everyday life, most direct input techniques are learned from those devices. We observed these actions when one of the participants slid her fingers on the map to zoom in. Thus, we used another task to determine whether intangible materials, such as air and projection images, can be reconciled with tangible materials as an interactive composite. A resizable circular shape was projected onto the surface. The majority of participants tried to squeeze the circle with both of their hands, as shown in Fig. 17. They replied, "This is quite funny—it feels like I'm squeezing pimples, and the air inside the display gives a totally different tactile sense compared to when I do the same with my touch pad." This response implies that intangible materials—air and immaterial, such as a projection image—can undoubtedly gain tangible materiality in successive composition.

Some participants attempted to grab the circle directly, as illustrated in Fig. 18. One of the participants mentioned, "The yielding and flexible quality of the inflated surface conveys a physical affordance to seize the displayed shape and minimize the size by grabbing it." Due to the slippery texture of the PVC balloon, it was not convenient for the participants to directly grab the shape directly. However, the fact that the prototype perceptibly afforded physical

Fig. 18 These two still images show participants attempting to directly grab the *circle* to reduce its size



interaction with its materiality was a noteworthy result of the practice in material composition.

7 Discussions and reflections

Each group engaged in an open-ended discussion after experiencing the prototype. Several qualitative questions were asked in questionnaire format. Participants were encouraged to answer the questions either by writing or by drawing on the given sheets or orally (Fig. 19).

The participants had their first experience with inflatable or flexible touch screens in the workshop. Eleven out of 15 participants were impressed by the Bubble Pop game due to the tactile feedback that they received from air. In addition, exploring spatiality, which they referred to as hidden space, by tilting the prototype in every direction made them more involved in the bodily interaction that is initially induced by Inflated Roly-Poly (Fig. 20). Some of the verbal feedback is listed as follows:

Fig. 19 Participants in group 4 discussed their experience with Inflated Roly-Poly and how it compares with the iPad's touch screen

- "Contrary to the rigid touch screens, Inflated Roly-Poly is undamageable by exertion gestures, so I thought that interacting with it could be an exercise per se."
- "The form factor design and softness of the air seems suitable for a children's toy."
- "The hemispherical bottom surface has inherent spatial interaction that goes well with navigation function in both the Bubble Pop game and map navigation."
- "Exploring the hidden space of the display was a unique feature that I haven't seen from any other flexible and touchable screens."
- "If the balloon part can have various shapes and size according to the context and user group, interactive applications will be more possible."

During the discussion, participants were asked to play MoleControlLite, which is a game that is similar to Bubble Pop, on an iPad. The moles disappear immediately when the screen is touched. Although the bubbles and moles employed different GUIs, the fundamental interactivity was identical in both games. The participants acknowledged the graphical difference. After they had played the MoleControlLite game for some time, we asked the participants to express their engagement level with both games as a percentage and inquired about the engagement gap that they perceived between the two media. The average level of engagement for participants who used Inflated Roly-Poly was twice the average level of engagement for participants who used the iPad (Fig. 21).

The two media contrasted in terms of distinguishable characteristics of tangibility. "I think the organic shape of the balloon merged with the materiality of the air enticed me to apply physical inputs, such as poking and punching, that I never experience with an iPad." One participant compared the two media as follows: "Both Inflated Roly-Poly and the iPad are interesting and enjoyable media for direct input interaction. However, the interaction technique should be coupled with the content that it supports. I think the Bubble Pop game was suitable for Inflated Roly-Poly because the metaphor of popping bubbles matches with the

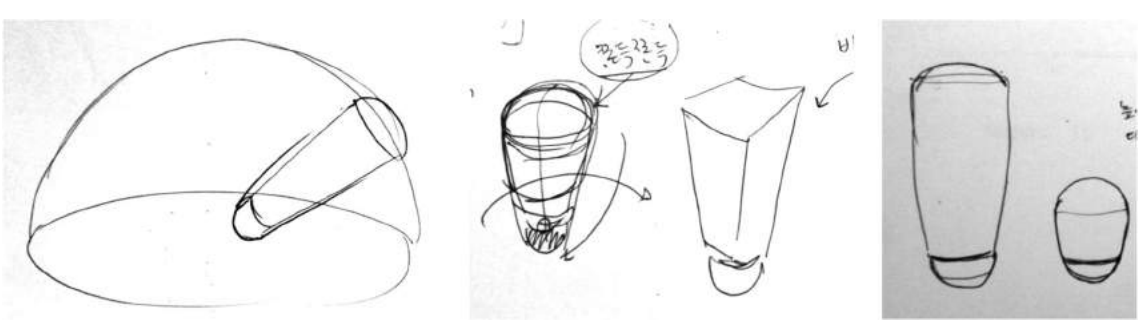


Fig. 20 Sketches from the participants: *left* expression of scanning half-sphere virtual space and *middle* and *right* recommended shapes and sizes of the balloon

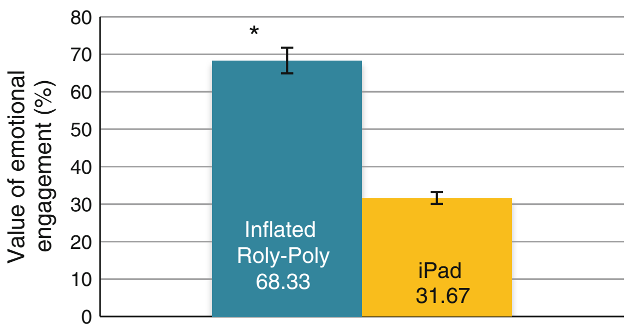


Fig. 21 Graph showing the significant engagement gap between the two media, as perceived by the participants, for the two devices. The emotional engagement value for Inflated Roly-Poly was 68.33 %, whereas the emotional engagement value of the iPad was 31.67 % (paired sample t test, $t = 8.54$, $*p < 0.001$)

poking gesture, and MoleControlLite game was also suitable for the iPad because it was not for physicality but fast and accurate control and response."

The discussion concluded with an in-depth ideation for further development of Inflated Roly-Poly. First, some participants proposed using various materials for prototypes because they were impressed by the tactile feedback. Rubber latex was the most desired material for the balloon because it is capable of supporting more flexible and malleable interactions and thoroughly transmitting the materiality of the air (Fig. 22).

The following quotes describe concepts generated by the participants:

- "If the projection area extends to an entire inflated body and if the prototype was much bigger, extreme sports-related interactions would be possible. I would love to do boxing games with interactive content displayed on the Inflated Roly-Poly."
- "It seems that no effort has been made in touchscreen-based devices and other related works of inflatable display to utilize full body movement as an interaction technique. The combination of air-filled display and hardware casing, with a hemispherical bottom part, affords physical actions. I want to use Inflated Roly-Poly for video chatting with my lover, so that I can hug and pinch him on the screen."
- "If the prototype also utilizes actuated movement that automatically leans the prototype's body by changing the center of gravity, it would become feasible to support mobile interaction as well. It will be able to change its direction without anyone touching it, or it can show people directions, similar to an interactive sign post or a kiosk installation."
- "The scanning of 3D hidden space seems to have potential for development. Navigating a galaxy in the heavens matches the half-sphere display that the prototype visualizes. It just feels like viewing the world through a window."
- "Since exerted force can be detected by a pressure sensor, a novel experience of drum play could be possible. The tilting and rotation angle could interactively coupled with pressure applied on the prototype to convey various types of sounds."

The participants' responses and sketches summarize the experience of *Inflated Roly-Poly* as follows:

1. A directly deformable inflated screen, which embodies materiality and tactility, invites physical interaction that is refreshingly entertaining.
2. The affordance of the roly-poly design leads participants to move the display spatially and introduces an innovative method for projecting interactive digital contents.

Inflated Roly-Poly manifests its novelty through its comprised materials. Tangible, intangible, and computational materials commingle to form a seamless integration as an interactive whole. Interaction occurs not only between the artifact and humans, but also among the materials. In the interactive demonstration, each material interacted with the other materials in different categories. Air in the PVC

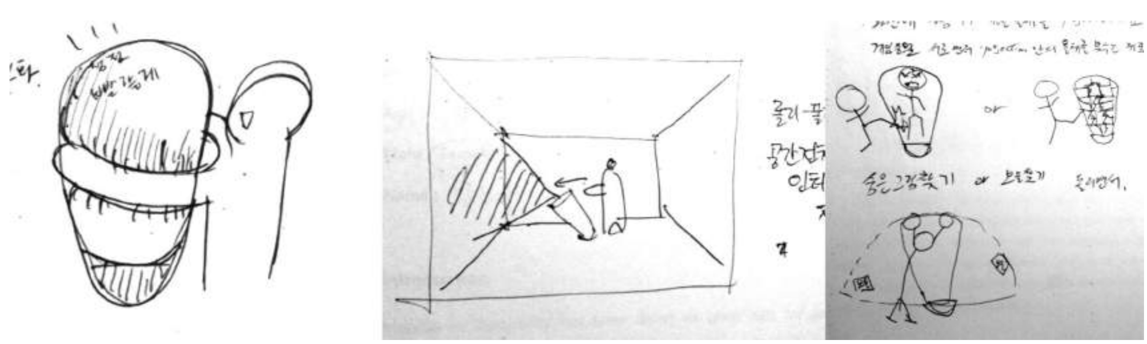


Fig. 22 Idea sketches by the participants: *Left* hugging the prototype interactively changes its status. *Middle* As an installation, the actuated Inflated Roly-Poly can behave like a robotic creature that simultaneously interacts with the user and environment. *Right* Exertion and spatial interactions proposed for the prototype with different scales

balloon generated passive haptic feedback via the surfaces that people touched, and an alteration of air pressure was sensed by digital information to be visualized as a display. This entire process was successful when intangible materials and immateriality wear materiality via material composition.

8 Conclusions

Material selection in the field of design has always been a critical issue, especially for traditional design objects that embody inherent physical and tangible qualities. Visual and tactile features of a material explicitly rendered on a surface express functional properties as well as aesthetical value. When design activity extends its domain into the digital realm, designers face the challenge of utilizing expanded material categories from physical to digital materials. Significant efforts have been made in the conventional TUI and OUI realms to bridge the physical and the digital. The majority of research has focused on input and output techniques toward the physical manipulation of digital information. We face the borderline of the next generation, in which material will shift into the center of interaction. *"Material can transform by itself to reflect and display changes in the underlying digital model serving as dynamic physical representations of digital information."* [22]

In this paper, we *proposed* a framework regarding material composition by reviewing tangible and interaction designs and by considering our previous design of Inflated Roly-Poly. We have demonstrated our effort to reveal a *trichotomy* categorization of materials that appear in interaction design projects. The initial perspective in establishing the theoretical framework was the notion that tangible, intangible, and computational materials are the essential substances that comprise the world in which we live. The particular aim of this paper is to convey the existence of intangible material and emphasize its role in interaction design. We technically reconfigured Inflated Roly-Poly, which is a tangible prototype that enables physical and spatial interaction via its form and material, as an artifact that is constructed based on the combination of three states. Thus, an intangible medium gains materiality via material composition with physical material and digital information. The participatory design workshop revealed that entangled practices for different categories of materials encourage the engagement of an innovative experience. We envision that the framework of material composition can offer different perspectives on implementing interactive systems as well as generate ideas of aesthetical interaction, which contribute to the future material interaction era.

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