# Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction

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## ABSTRACT
Our current understanding of human interaction with hybrid or augmented environments is very limited. Here we focus on 'tangible interaction', denoting systems that rely on embodied interaction, tangible manipulation, physical representation of data, and embeddedness in real space. This synthesis of prior 'tangible' definitions enables us to address a larger design space and to integrate approaches from different disciplines. We introduce a framework that focuses on the interweaving of the material/physical and the social, contributes to understanding the (social) user experience of tangible interaction, and provides concepts and perspectives for considering the social aspects of tangible interaction. This understanding lays the ground for evolving knowledge on collaboration-sensitive tangible interaction design. Lastly, we analyze three case studies, using the framework, thereby illustrating the concepts and demonstrating their utility as analytical tools.

### Author Keywords
Tangible Interface, Tangible Interaction, CSCW, Design, Analysis, Framework, Collaboration, Social Interaction

### ACM Classification Keywords
H5.2. User Interfaces, H.5.3. collaborative computing

## INTRODUCTION
*Tangible User Interfaces* (TUIs) and *Tangible Interaction* are terms increasingly gaining currency within HCI. This field of research relies on tangibility and full-body interaction and gives computational resources and data material form. Embedding computing in the everyday environment and supporting intuitive use, it shares goals with other novel approaches to HCI. Variations of this approach have been pursued over the last two decades as 'graspable user interfaces' [13], 'tangible user interfaces' [34], 'tangible interaction' [5, 8], or physical-digital interactions and digitally-augmented physical spaces [26].



While in traditional desktop computing the screen is merely a window through which we reach into a digital world, with tangible interfaces we act within and touch the interface itself. Designing tangible interfaces requires not only designing the digital but also the physical, and their interrelations within hybrid ensembles, as well as designing new types of interaction that can be characterized as full-body, haptic, and spatial - new challenges for design and HCI. As building upon users' experience of interacting with the real world lowers the threshold for activity, the embodiment of interaction objects alleviates the 'access bottleneck' of the keyboard [31], and interaction with these systems is easily observable, they lend themselves to the support of face-to-face social interaction. This is reflected in a considerable number of systems aimed at cooperative scenarios [1, 7, 26, 31, 32, 33, 36] (see also [34]).

Until recently, research on TUIs focused on developing new systems. A move towards concepts and theory can be detected from a journal special issue on 'tangible interfaces in perspective' [18]. However, attempts to develop frameworks have concentrated mainly on defining terms or on categorizing and characterizing systems (e.g. [3, 12, 30, 34]). While supporting structural analysis, mapping out the design space and detecting uncharted territory, these offer little advice when designing for real world situations and seldom address users' interaction experience. Despite many interesting explorations of technical options, there is still a need for conceptual frameworks that unpack why 'tangible interaction' works so well for users [9]. Equally there is a need for principled approaches supporting research and design of these new hybrid environments that are inherently 'socially-organized settings', as Williams et al note [36].

We have chosen to use 'tangible interaction' as an umbrella term for this field, drawing together several fields of research and disciplinary communities who can profit from each others' distinct perspectives and knowledge. Tangible interaction, as we understand it, encompasses a broad range of systems and interfaces relying on embodied interaction, tangible manipulation and physical representation (of data), embeddedness in real space and digitally augmenting physical spaces [4, 5, 6, 8, 26, 34]. It encompasses approaches from HCI, computer science, product design and interactive arts. The proliferation of computing into everyday appliances draws product designers towards IT product design [5, 8]. Artists and museums experiment with hybrid interactives [4, 6, 28, 36]. Increasingly systems are developed by users, e.g. from architecture or biology. This becomes even more important with computing moving beyond the desktop and 'intelligent' devices spreading into all areas of life and work. Applications previously not considered 'interfaces' are turning into such and computing is increasingly embedded in physical environments. Thus a conceptual understanding of this new interface type and knowledge to support design becomes even more important.

In this paper we introduce a framework that focuses on the user experience of interaction and aims to unpack the interweaving of the material/physical and the social aspects of interaction. The presented framework thereby contributes to the larger research agenda of *Embodied Interaction* [9, 27, 36]. The framework offers four themes and a set of concepts that aid in understanding the interaction with tangible interaction systems and in designing for the support of social interaction. It builds upon results from a PhD project [19] and recent studies in related areas [21, 22]. One theme has been described in detail in [20].

In the next section we introduce our notion of 'tangible interaction', which builds upon and encompasses approaches from different disciplines. We also give an overview of related work, identifying the knowledge gaps which motivated our research. Then we introduce our framework, which offers four themes that are each elaborated by a set of concepts. We then present three case studies and use the concepts to discuss them. We conclude with a discussion of the framework and related work.

## RELATED WORK ON TANGIBLE INTERACTION

We now give an overview of the dominant views and approaches within different disciplines on 'tangible interaction' and propose a deliberately broad, encompassing view. We then move on to previous frameworks and research on collaboration as application field for tangibles.

### A broad view on tangible interaction

A look at the viewpoints of the research disciplines and approaches mentioned above reveals that the definition of 'tangible interfaces' frequently used in HCI is too narrow to encompass these. From the characterizations found in literature, we can distinguish a data-centered view, pursued in Computer Science and HCI; an expressive-movement-centered view from Industrial and Product Design; and a space-centered view influenced from Arts and Architecture:

- *Data-centered view*: Ullmer and Ishii and others in HCI [9, 18, 34] define 'tangible user interfaces' as utilizing physical representation and manipulation of digital data, offering interactive couplings of physical artifacts with "computationally mediated digital information" [18]. This characterization of tangible interfaces is frequently cited in HCI publications. Conceptual research from HCI and computer science often explores possible types of coupling and representations [34]. A variant of this view explores different types of couplings and transversals between the digital and the physical [26].
- *Expressive-Movement-centered view:* An emerging 'school' in product design aims to go beyond form and appearance and to design the interaction itself. This view emphasizes bodily interaction with objects, exploiting the "sensory richness and action potential of physical objects", so that "meaning is created in the interaction" [8]. Design takes account of embodied skills, focuses on expressive movement and 'rich' interaction with 'strong specific' products tailored to a domain [5, 24]. The design community prefers the term 'tangible interaction'.
- *Space-centered view:* Interactive arts and architecture increasingly talk about 'interactive spaces' and build installations based on spatial interaction. 'Interactive/ interactivating spaces' rely on combining physical space and objects with digital displays or sound installations [4, 28]. "Interactive systems, physically embedded within real spaces, offer opportunities for interacting with tangible devices", and so "trigger display of digital content or reactive behaviors" [6]. Full-body interaction and use of the body as interaction device and display are further typical characteristics of this approach.

*Tangible interaction,* as we understand it, encompasses a broad range of systems and interfaces, building upon and synthesizing these views. These share the following characteristics: tangibility and materiality, physical embodiment of data, embodied interaction and bodily movement as an essential part of interaction, and embeddedness in real space [4, 5, 6, 8, 9, 18, 34]. Tangible interaction encompasses approaches from HCI, computer science, product design and interactive arts.

This concept of *tangible interaction* has a broader scope than Ullmer and Ishii's description of tangible interfaces: "giving physical form to digital information" and its subsequent physical control [34], which is often used as a definition of TUIs (data-centered view). Tangible interaction is not restricted to controlling digital data and includes tangible appliances or remote control of the real world [24]. This approach focuses on designing the interaction itself (instead of the interface) and on exploiting the richness of bodily movement [5, 8]. Interaction with 'interactive spaces' by walking on sensorized floors or by simply moving in space [4, 28] further extends our perspective on 'tangible' interaction, the body itself becoming an input 'device'. Instead of using a restrictive definition that excludes some of these interesting system variants (often crossing categories, e.g. [28]), it seems more productive to address this larger design space. Thereby we leave the somewhat artificial confines of any definition behind, and interpret these attempts at conceptualization as emphasizing different facets of a related set of systems. We believe the field will benefit from this encompassing approach.

### Related work on 'tangible' frameworks and tangible collaboration support

Previous attempts to develop frameworks for tangible interfaces/action have focused mainly on defining terms, categorizing and characterizing systems, or on types of coupling: Ullmer and Ishii [34] provided the first attempt to categorize systems and representations; Holmquist et al [17] discussed a vocabulary of tangible interaction objects; Fishkin interprets tangibility as a two-dimensional design space of embodiment (distance input-output) and metaphor (similarity of interaction, iconicity) [12]. Benford et al map out the relation between what systems can sense and what is sensible or desirable [3] to detect uncharted territory. Wensveen [35] proposes a framework on legible mappings between user actions and mediated effects. Most frameworks take a structural approach, systematically mapping out an abstract design space, but seldom address the human interaction experience. Other basic research focused on the usability of manual handling, e.g. on advantages of bimanual action and 'spatial multiplexing' of input devices [13]. We return to our framework's relationship to earlier attempts at understanding tangible interaction in the final discussion. The most notable push towards a theory of tangible interaction that contributed to understanding the interaction experience was provided by Dourish's book on 'Embodied Interaction' [9]. Dourish emphasizes how social action is embedded in settings, which are not only material, but also social, cultural and historical, focusing on the social construction of meaning. While the social has been elaborated, materiality and its relation to the social have been less discussed.

The support of social interaction and collaboration might be the most important and domain-independent feature of tangible interaction, but this issue has attracted little explicit attention. The pioneering work of [1, 32], analyzing social use of TUIs and identifying social affordances, found few followers. Even though many researchers agree that TUIs are especially suited for collocated collaboration and build systems for such scenarios [7, 26, 31, 34], conceptual papers often only briefly mention visibility of actions and distributed loci of control as collaborative affordances. Evaluations (even of systems aimed at group use) often assess individual use, focusing on task effectiveness, or give primarily anecdotal accounts of field use without sufficient detail to discern what exactly contributes to the success of systems. Relevant studies often stem from overlap with tabletop interaction research [29], which as a field is being propagated by CSCW researchers, but does not investigate tangibility as a core issue.

The research community therefore lacks concepts for analyzing and understanding the social aspects of tangible interaction and design knowledge on how to design so as to support social interaction and collaboration. This has motivated the development of our framework, which takes a more phenomenological perspective on the interaction experience, focusing on social interaction while addressing the broader design space of 'tangible interaction'.

## OUR FRAMEWORK ON TANGIBLE INTERACTION

The framework is structured around four themes (figure 1) that are not mutually exclusive, but interrelated, offering different perspectives on tangible interaction. A set of concepts elaborates each theme, providing more concrete handles for understanding their implications. Themes are:

- *Tangible Manipulation* refers to the material representations with distinct tactile qualities, which are typically physically manipulated in tangible interaction.
- *Spatial Interaction* refers to the fact that tangible interaction is embedded in real space and interaction therefore occurrs by movement in space.
- *Embodied Facilitation* highlights how the configuration of material objects and space affects and directs emerging group behavior.
- *Expressive Representation* focuses on the material and digital representations employed by tangible interaction systems, their expressiveness and legibility.

Frameworks in general serve to focus our view, providing us with concepts that systematize our thinking and allow for reflection. We feel that our approach is distinct from other frameworks by not offering taxonomies, but perspectives and themes for analysis and conceptual guidance for design. Taking these perspectives allows for systematic shifts of focus and has us look through different lenses, highlighting different aspects of one object. The themes and the related concepts have been developed over the course of several years, summarizing our experiences from system assessments and reflections on design, in combination with an extensive literature review on the use of material artifacts in social situations (as highlighted by the theory of distributed cognition [16, 23, 25] and many work studies), distilling a set of social affordances [19]. The overall framework is thus the result of a synthesis of previous work by other researchers and concepts developed by us. Recurrent themes or insights from the literature have been integrated and fused into a larger framework that focuses on the (social) use experience of tangible interaction.

The graphic (figure 1) can be read from left to right as referring to the design space of tangible interaction from the specific to the general. *Tangible Manipulation* is the most specific theme, relying on the use of material objects. It applies best to systems usually referred to as tangible interfaces [34] and tangible appliances. *Spatial Interaction* and *Embodied Facilitation* provide insights relevant for the broader research area of 'embodied interaction' [9], where movement in space and physical configuration of computing resources are central characteristics, e.g. mobile interaction and ubiquitous computing. *Expressive representation*, insofar as it concerns tangible representations, is specific to tangible interaction, but can be generalized to Mixed Reality representations.

The *Embodied Facilitation* and *Spatial Interaction* themes are those most concerned with understanding and supporting social interaction. The remaining themes address

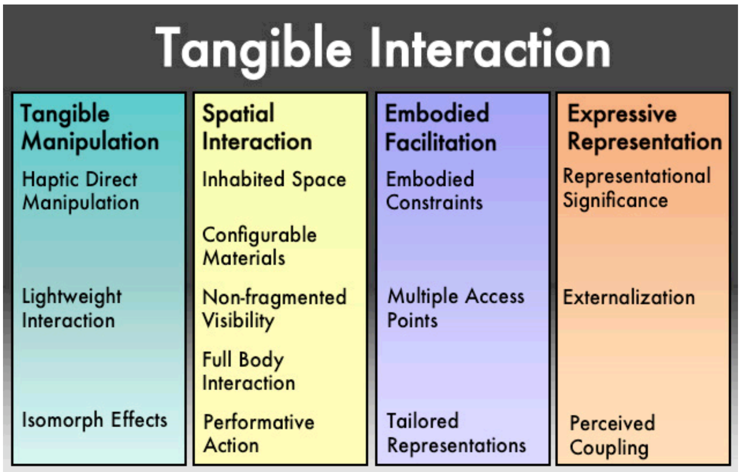


**Figure 1. Tangible Interaction Framework with themes and concepts**

aspects of the user experience that support social interaction in indirect ways, e.g. by lowering participation thresholds, making action publicly available, or providing shared references, while being important for single users as well.

The framework is organized on three levels of abstraction. The themes offer perspectives at an abstract level and define broad research issues such as the role of space. Themes are each elaborated by a set of concepts that provide analytical tools for describing empirical observations, summarize generic issues, and help to pinpoint design mistakes and successes or to guide design on a conceptual level. A level of more directly applicable design 'guidelines' is in development for practical purposes. These provide 'design sensibilities' [6, 14], through inspiring and thought-provoking suggestions. Here we give a high-level overview of the framework, focusing on its analytical and conceptual contribution to understanding and designing tangible interaction, while the presentation of guidelines will have to wait for later papers.

We now present the four themes in more detail, first explaining each theme's relevance for tangible interaction, then laying it out in detail and finally summarizing the related concepts (see Figure 1), characterizing each with a short question in colloquial language.

### Theme: Tangible Manipulation (TM)

Tangible Manipulation is bodily interaction with physical objects. These objects are coupled with computational resources [33], allowing the user to control computation.

Tangible Manipulation involves *directly manipulating* material objects that represent the objects of interest (unlike a mouse that acts as a generic and transient intermediary) [33]. These objects are simultaneously interface, interaction object and interaction device (for this distinction see [2]). We termed this *haptic direct manipulation*. One manipulates the interaction objects, has tactile contact, feels haptic feedback and material qualities. Tangible objects can invite us to interact by appealing to our sense of touch, providing sensory pleasure and playfulness.

We have found [10] that a good representation is not sufficient for supporting discussion groups if there are no *lightweight* means of creation and manipulation. These provide focus, allow for creating shared visions and make these discussable. *Lightweight interaction* creates a 'conversational' style of interaction, giving constant feedback, allowing users to proceed in small steps, and to express and test their ideas quickly.

Directness can also refer to the relation between the manipulation of interaction devices and the acted-upon objects as well as eventual effects [2]. *Isomorph effects* that preserve the structure of the user's manual actions by e.g. being close in time, visible nearby or of the same shape, are easily legible (cf. [35]). If data is physically represented and manipulated, this is often provided. Yet, we feel that too many tangible interfaces aim for direct one-to-one mappings, remaining literal and missing out opportunities for employing magical metaphors or for providing the user with computational re-representations of information [26] and transformations of input (highlighted by the theory of distributed cognition [16, 23, 25]). While aiming to exploit tangible objects' strength of providing legible relations between cause and effect, we simultaneously warn of stopping at simple, direct mappings. If tangible interaction is to become useful for complex domains and to scale up to real-world size examples, balancing legibility and computational power is one of the grand challenges. The main concepts, colloquially phrased, are:

*Haptic Direct Manipulation:* Can users grab, feel and move 'the important elements'?

*Lightweight Interaction:* Can users proceed in small, experimental steps? Is there rapid feedback during interacting?

*Isomorph Effects:* How easy is it to understand the relation between actions and their effects? Does the system provide powerful representations that transform the problem?

### Theme: Spatial Interaction (SI)

Spatiality is an inherent property of tangible interfaces. They are embedded in space, take up real space, are situated in places, and users need to move in real space when interacting. Interaction with spatial installations or interactive spaces can be interpreted as a form of tangible interaction that is not restricted to touching and moving objects in space, but relies on moving one's body. Issues of spatiality have been little discussed so far for tangible interfaces. Sharlin et al [30] argue that manipulating tangible objects exploits intuitive human spatial skills and conclude that good spatial mappings between objects and the task are essential, suggesting inherently spatial domains as most appropriate for TUIs. Broader views on spatiality that take social aspects into account (for example Dourish and Robertson [9, 27]) are rare.

We cannot escape spatiality - we dwell, act and meet each other in space; it is our habitat (Merleau-Ponty). Being spatial beings, our body is the central reference point for perception. Movement and perception are tightly coupled and we interpret spatial qualities, such as the positioning of objects, in relation to our body. Spatial relations therefore have psychological meaning and affect our perception of a setting. Real space thus is always *inhabited* and situated in context, a meaningful *place* [6, 11, 36] with atmosphere and history. Engaging in tangible interaction usually means moving objects around or moving oneself. *Configurability* refers to the meaningful re-arrangement of (significant) objects whereby the user controls or explores the environment (cf. [9, 13]). Not all of these arrangements need to be tracked by the system. Some may serve idiosyncratic, emergent needs of users or deliberately take place 'out of bounds' of the tracking range [3, 7, 25].

In contrast to most attempts in tele-communication, real space provides *non-fragmented visibility*. This allows us to see someone pointing, and to seamlessly follow the gesture with our gaze, not fracturing the picture; it provides a reciprocal situation where seeing implies being seen [27]. Interacting in real space furthermore has the potential to employ *full-body interaction*, asking for large and expressive, skilled body movement [5, 24] that has meaning in interacting with the system, that is observable and intelligible, that acquires communicative and *performative* function [27, 36]. Performativity implies that the detailed HOW of doing something is an integral part of the action's communicative effect. Such performances take part in how we encounter other humans. As an aside, performativity can be enhanced by tangible manipulation, as the material objects are visible as well and may require large movements. The main concepts for Spatial Interaction are:

*Inhabited Space:* Do people and objects meet? Is it a meaningful place?

*Configurable Materials:* Does shifting stuff (or your own body) around have meaning? Can we configure the space at all and appropriate it by doing so?

*Non-fragmented Visibility:* Can everybody see what's happening and follow the visual references?

*Full-Body Interaction:* Can you use your whole body?

*Performative Action:* Can you communicate something through your body movement while doing what you do?

**Theme: Embodied Facilitation (EF)**

With tangible interaction we literally move in physical space and metaphorically in software space. These define structure that facilitates, prohibits and hinders some actions, allowing, directing, and limiting behavior. Structure thereby shapes emerging social configurations. Tangible interaction embodies structure and thereby styles, methods and means of facilitation. We can learn from facilitation methods how to shape physical and procedural structure so as to support and subtly direct group processes (for details see [20]).

The concept of *embodied constraints* refers to the physical system set-up or configuration of space and objects. Embodied constraints (such as size, form, or location of objects, cf. [29]) ease some activities and limit others, determining trajectories of action or providing implicit suggestions. The options to access and manipulate relevant objects provide *access points*. We can analyze systems in terms of the resources offered for observing, accessing, and interacting with the objects of interest, and in terms of privileges and restrictions. *Multiple access points* distribute control, keep individuals from taking over control, and lower thresholds for shy people. *Representations that are tailored for user groups* can address and engage participants, offering cognitive and emotional access. While intuitiveness of interaction is helpful in the first encounter with the system, in the long run simple intuitiveness neglects users' skill (cf. [5, 24]) and does not scale to experienced users and complex domains. While new users should be able to quickly explore the basic syntax of interaction when manipulating objects, the semantics and refined interaction syntax may rely on domain knowledge, experience, and skill. The main concepts in this theme are:

*Embodied Constraints:* Does the physical set-up lead users to collaborate by subtly constraining their behavior?

*Multiple Access Points:* Can all users see what is going on and get their hands on the central objects of interest?

*Tailored Representation:* Does the representation build on users' experience? Does it connect with their skills and invite them into interaction?

**Theme: Expressive Representation (ER)**

Tangible Interaction is about physical representation of digital functions and data, or of other physical objects (tele-control). Often hybrid representations combine material and digital elements, each having different representational qualities, e.g. projections onto tangible objects or spatial sound. In interaction we 'read' and interpret representations, act on, modify, and create them.

As humans we create and share *externalizations* of our thinking that aid cognition, provide shared reference implicitly or explicitly, augment our talk, remember our traces, and document common ground [16, 23, 25]. Ullmer and Ishii [34] introduced the term *representational significance*, referring to physical tokens that embody essential aspects of the system state so it is legible for users (even without digital representations). We extend and refine this notion as referring to the *interrelation* of physical and digital representations and to how users perceive them. We have found that users perceive a tangible interface as "not very tangible" and the tangible objects as insignificant, if these were only of temporary relevance or not expressive [10]. Clearly the effort of producing tangible

**Figure 2. The EDC: (left to right) handing over a pen at the SmartBoard, using tangible tokens on the PITA-BOARD to create a new bus stop, multiple interaction objects on the re-designed PITA-BOARD, and highlighting overlaps of desired walking distance**

representations that take up 'interface estate' has to be justified by their relevance – either in their tangibility being a salient part of the representation (e.g. emphasizing 3D-ness or material qualities) or in effecting the style of interaction. Thus these interactions should not be peripheral, but need to be salient to the overall use process. If we aim for tangible interaction, tangibility as well as the hybridism of the system should be noticeable and not be overshadowed or invisible. Legibility of system reactions and experience of the system as being hybrid are enhanced by a *perceived coupling* between physical objects and digital representations and between user actions and effects - a kind of faked causality. Here the main concepts are:

*Representational significance:* Are representations meaningful and of long-lasting importance? Are physical and digital representations of the same strength and salience?

*Externalization:* Can users think and talk with or through objects, using them as props to act with? Do they give discussions a focus and provide a record of decisions?

*Perceived Coupling:* Is there a clear link between what you do and what happens? Are physical and digital representations seemingly naturally coupled?

## THREE CASE STUDIES

We now present case studies and discuss these along themes and concepts, mostly following the order in which themes were presented previously. (TM), (SI), (EF), and (ER) denote the respective themes that concepts refer to. The main aim here is to demonstrate how the framework supports analysis, highlights strengths or weaknesses of analyzed systems, and points out useful design directions.

One of the authors has been involved partly in the development of the system from case study 1. With the other systems we became involved for evaluation, after these were installed. This first-hand access to use data and observations seems essential for an analysis of (social) use experience. All case studies are second-level reflections of the original studies [10, 19, 21, 22] that helped us develop this framework. See also [20] for a deeper analysis of the cases along one theme, Embodied Facilitation.

### Case study 1: The EDC assessment

The ENVISIONMENT AND DISCOVERY COLLABORATORY (EDC) has been developed at the Center for Lifelong Learning and Design (L3D) at the University of Colorado, Boulder to support co-located participatory urban planning [1]. The situation designed for can be characterized as collaborative design and (conflict) negotiation, problem solving, and establishing shared understanding. The EDC provides an augmented game board that allows tangible interaction with projected computational simulations on an aerial photo. The first author collaborated with L3D members on evaluation and redesign of this system [10, 19]. Two system versions were available for a comparative assessment (see figure 2). One uses a horizontal SmartBoard™ that allows drawing with fingers to create, move or delete objects and pen sketching, but cannot handle simultaneous events or detect physical objects. The second, newly developed version was termed PITA-BOARD. It is based upon a chessboard grid (http://www.dgtprojects.com) that registers RFID tags embedded in objects and comes closer to the idea of interaction by tangible manipulation.

The chosen scenario was the redesign of a local bus route by neighborhood residents. The systems were assessed by letting two groups use them in a role-play of a facilitated neighborhood meeting with identical discussion structure. The groups first discussed the current bus route, then how far they would be willing to walk to a bus stop, looked at options for a new route, and finally decided on a route and placement of stops. The system supported this discussion with various interactive representations and simulations. The sessions and a subsequent discussion were videotaped and an interaction analysis carried out. Assessment results guided re-design of the PITA-BOARD, which was presented at various occasions, providing its designers with user feedback and opportunities to observe users. This experience was reflected upon to determine whether re-design decisions were successful or needed rethinking.

#### *Reflecting on the EDC*

In the original assessment of the PITA-BOARD, participants commented on the system as not being very tangible and tangible tokens as feeling rather irrelevant. We could trace this back to some of our design decisions. For example we had handed out one token that would 'stamp' generic bus stops. For the revised version we provided one bus stop token per allowed stop. User feedback now emphasized the systems tangibility 'You felt invited to grab and interact' and we could observe rapid interactions. This design decision made relocating a stop a matter of simply lifting up and placing it. The bus stops as the objects of interest could now be *directly manipulated* in a *lightweight* way (TM). Physical tokens were *meaningfully configurable* (SI), e.g. bus stop tokens were sorted in inbound and outbound stops prior to placement. With the SmartBoard version, sketching proved to be an important *lightweight* means for the group to express and negotiate ideas. This facility was missing with the PITA-BOARD, creating difficulties in establishing shared understanding.

Assessment of the EDC led to the discovery of the theme of *Embodied Facilitation*, realizing that seemingly trivial design decisions (such as system size, placement and number of tools) had huge impacts on group behavior and dynamics. *Embodied constraints* (EF) were given by the sheer size of the SmartBoard, necessitating mutual helping, coordination, and handing over of tools (pens), thereby indirectly fostering collaboration and awareness. This also made it physically impossible for one person to take over control of the entire board. Participants felt these to be valuable effects and advised us to keep the system that large. With the much smaller PITA-BOARD we observed markedly less of these behaviors. Lessons learned for re-design included enlargement of the PITA-BOARD. We now also consciously provided enough tools for several participants to be active at once, but only a restricted number, so they would need to help each other and coordinate use. The provision of multiple tokens increased *access points* (EF), thus distributing control and lowering thresholds for shy people to become active. In the PITA-BOARD assessment session one participant had retained the bus stop tool and 'stamped' all stops. With multiple tokens this is less easy and would obviously be impolite. The size of the SmartBoard and the redesigned PITA-BOARD furthermore required large movements and gestures from participants (*full body interaction*), which became very expressive and lively (SI). This was commented upon as enlivening and less tiring than 'sitting and clicking'. Sketching on the SmartBoard had been a powerful means of *externalization* (ER), helping the group to think and communicate while providing a trace of their discussion. Some of our interactive visualizations provided additional computational support by e.g. calculating the route length or highlighting overlaps of acceptable walking distances to bus stops from homes. The redesign of the PITA-BOARD put emphasis on enhancing *representational significance* (ER), making tokens more meaningful. In the original version, for one type of token both the physical object and its 'digital icon' showed a house. If the token was used for other purposes such as selecting the desired walking distance, the icon stayed in place. This was changed to a complementary constellation of a tangible human figurine and a house icon. Tangible bus stops as well, being stand-in representations, had more significance than the previous generic tool.

### Case Study 2: The Sensoric Garden CLAVIER

Seven installations created by students were shown on three nights in summer 2002 at a public festival in a park in Bremen [21]. Here we focus on the CLAVIER (figure 3): a walkable keyboard and audio installation installed on a path. Walking along the path interrupted light sensors, triggered colorful spotlights and different drums and beats, producing an ambient sound environment. This installation attracted a lot of curiosity, as visitors became aware quickly of the effects triggered from movement. They inspected the sensors and consciously triggered them. Later in the night, visitors danced to the music, jumped from light to light and composed. Some danced for extended periods of time (withstanding steady rain drizzle) and in groups. Others used umbrellas to trigger multiple sensors. The CLAVIER provided a simultaneously passive and active experience as people danced to the music they were creating. Among all installations, the CLAVIER attracted the most interaction and a constant gathering of observers. Even though it was easy to understand the general concept of interaction, as light sensors were located directly underneath spotlights and taped stripes marked the sensor areas acting as 'keys', a good performance required practice or skill. The entry threshold nevertheless was small, as one just needed to walk on the path and sound effects were always pleasing.

#### *Reflecting on The CLAVIER*

Moving along the CLAVIER path was *lightweight* (TM), as even incidental interaction from passing the path provided pleasing effects. The positioning of spotlights above sensors and immediate visual-auditory feedback provided visitors with sufficient *isomorph structure* (TM) to understand the basic functionality. This also ensured *perceived coupling* (ER) through the visual-auditory unity of input and output space and time. Yet input was also *transformed* into a new medium: music, exploiting computation that ensured a pleasing soundscape. *Representational significance* (ER)

**Figure 3. Visitors exploring the CLAVIER and dancing on it in the rain, showing co-located feedback and multiple input loci**

was provided by the keyboard being visible and legible, unifying light (digital effects) and space (physical form) into one meaningful environment.

The CLAVIER well illustrates the spatial interaction theme. The expressive and *performative* aspects of *full-body interaction* (SI) formed an essential part of the experience. People walked back and forth, jumped and danced for extended periods of time alone and in groups. By necessitating large-scale bodily interaction, interaction was transformed into a *public performance*. While each single action was simple and effects legible, the contextualization of actions by location (different light and sound effects) provided a deep and varied 'interaction space' that visitors navigated with their body. This also provides an example for multiple points of interaction. Instead of using objects, the visitors' bodies here took the role of interaction devices or objects, being *configured* in space (SI). While not haptic in a literal sense, this is very *direct interaction* (TM). *Access points* to the keyboard (EF) were distributed, allowing several persons to be active. This allowed for incidental simultaneous activity, cooperative dancing and composing. To interact as a group seemed to be fun in itself. In several ways the system encouraged implicit and explicit collaboration. Passersby inadvertently interacted with intentional 'composers'. Furthermore the CLAVIER's sheer size acted as an *embodied constraint* (EF), necessitating the activity of several people to produce a complex soundscape, as a single person could only trigger a few adjacent sounds (similar to the installations from [33]). The installation in this way encouraged group creativity, requiring and requesting collaboration and coordination.

### Case Study 3: The medien.welten exhibition

An evaluation by the first author of a museum exhibition in Vienna on media evolution provides the third case study [22]. The exhibition combined traditional object exhibits with digital and hybrid interactives, turning the exhibition space into a computationally augmented space offering opportunities for tangible interaction. Traditional object exhibits were placed next to interactive hands-on exhibits. The ABACUS (fig. 4 right side) consisted of a board with physical beads; a computer screen placed behind it guided visitors through calculation examples. Another exhibit had visitors use an alphabet wheel for telegraphy or ticker Morse code. Five touch screens offered a guide system, others served as information terminals. Very popular was a blue screen TV NEWS STUDIO where visitors were led through reading the news and could videotape themselves, overlaid with the local TV logo. Furthermore ten computer terminals offered a range of applications.

#### *Reflecting on the exhibition installations*

Some of the interactive hands-on exhibits such as the ABACUS and the telegraphy exhibit allowed for tangible, *haptic direct manipulation* (TM). These exhibits were among the most popular (determined by observation and logfile analysis) and were used by visitors of all ages. Most other exhibits had clearly distinct user groups; teenagers and children being primarily interested in digital interactives and senior citizens focusing almost exclusively on traditional exhibits. Tangible Manipulation thus seems to offer a strategy for museum interactives that attract a diversity of visitors, making both new and 'old-fashioned' technologies accessible and engaging.

Similar to other authors in HCI and CSCW we found the museum visitor experience to be of social nature. Observation revealed how different types of installations attracted different visitor constellations and interaction patterns, engendered by the physical set-up of installations. While touch screens or terminals were used dominantly by one visitor and only rarely by two, interactive and hands-on installations were often surrounded by groups of up to five people, who often interacted in parallel, profiting from interaction being observable, with observers commenting and scaffolding. Figure 4 shows a family of four at the ABACUS, illustrating how size and form as a specific type of *embodied constraint* (EF) limit the number of people able to focus on it. Several visitors can move the physical beads at once and the set-up provides *access* for observers. The blue screen TV studio, large and publicly *visible*, attracted many observers standing along a long aisle that led to the podium and parted observers from interactors, with spatial relations that are interpreted subconsciously (SI, EF). Its public visibility transformed visitors' interaction into a public *performance* (SI), more challenging than the CLAVIER, but nevertheless enjoyed by visitors who often deliberately exaggerated and were very keen to use it.

## DISCUSSION

The discussion of case studies indicates that some themes are more relevant for certain application areas; therefore the analysis of some case studies drew more on these themes. 'Externalizations' seem most relevant when the design aim is to support communication, negotiation, and shared

**Figure 4. Telegraphy hands-on exhibit, the blue screen TV News studio, and a family exploring the ABACUS hands-on exhibit**

understanding (EDC case study), where performative interaction supports implicit communication and awareness. For public spaces or entertainment-related areas performativity plays a larger role in drawing people's attention and being part of the 'content' of interaction. Use of the framework draws attention to some opportunities in the design – e.g. employing haptic direct manipulation for museum installations as a strategy to lower access thresholds and engage visitors. While the installations did this to some degree, they did not exploit computational re-representations (they were limited in the scope of effects) or let visitors configure things (e.g. move tangible objects around and thereby effect the larger museum space).

In literature, frameworks presented hitherto have aimed to enhance design for either social interaction or tangible interfaces. Few have combined both issues. Our framework shares characteristics with others that offer 'design sensitivities' and support designing for social interaction [6, 9, 14]; it is similar in that it is not prescriptive, and thus needs to be interpreted and appropriated for concrete situations. It contributes to the larger research agenda of *Embodied Interaction* [9, 36], providing insight into the relation of embodied and social interaction. While sharing goals with Dourish [9], our view on embodiment is rather influenced by Merleau-Ponty's phenomenology, seeing the body as center of pre-reflective, yet intentional and interpretative human perception and experience (cf. [27]). With the themes of Embodied Facilitation and Spatial Interaction we reconcile the notions of place and space, uncovering their interrelation. *Embodied Facilitation* lends attention to the ways in which geometric, structural qualities predetermine and guide interaction, affecting how space becomes appropriated, inhabited, and experienced. This is related to the notion of 'social affordances' [15] and Erickson's early reflections [11], interpreting space as an interface that structures human interaction. The notions introduced here contribute to the development of heuristics to help answer questions like the impact of systems' form factors on interpersonal interaction, making concrete some of the guidelines given in [29] for tabletop interaction.

Our framework integrates and fuses relevant recurrent themes and concepts from previous attempts at conceptualizing tangible interaction. For example the seminal work of Fitzmaurice [13] addressed issues strongly related to the tangible manipulation theme, albeit focusing on the usability and effectiveness of haptic directness. Our concept of *configurable space* owes to his notion of 'spatial multiplexing' and spatial reconfiguration [13], and to Dourish's highlighting of tangible computing properties [9]: distributed locus of control and the opportunity for users to configure computing by exploiting the relationship of actions and space. Like us, Ullmer [33] analyzed the use of physical constraints, but aimed predominantly at easing interaction with TUIs. In recent years more emphasis has been directed to the aesthetic and expressive aspects of manual interaction with objects [5, 8, 35]. Yet these attempts have mostly investigated the individual user experience. While all of these are important contributions that have inspired us, they often considered isolated aspects. Our aim has been to integrate these into a wider framework that focuses on the overall (social) use experience.

## CONCLUSION

Currently, research has a limited understanding of human interaction with hybrid or digitally-augmented environments. In this paper we focused on 'tangible interaction', an approach that relies on embodied interaction, tangible manipulation, physical representation, and embeddedness in space. Our aim has been to develop a better understanding of the user experience of tangible interaction and concepts for analyzing its social aspects along with knowledge aiding collaboration-sensitive design. We have presented a deliberately non-restrictive view of 'tangible interaction' that encompasses approaches from different disciplines. The framework introduced here is structured around four themes and a set of corresponding concepts. It provides perspectives that aid in analysis and design by enabling systematic shifts of focus and highlighting relevant themes, rather than banking on a taxonomy. For this paper we focused on the overall framework and its themes and concepts. The *Tangible Manipulation* theme refers to the reliance on material representations typical for tangible interaction. *Spatial Interaction* focuses on how tangible interaction is embedded in space and occurs in space. *Embodied Facilitation* highlights how configurations of objects and space affect social interaction by subtly directing behavior. *Expressive Representation* focuses on the legibility and significance of material and digital representations. We then introduced three case studies and discussed them using the themes and concepts, thereby illustrating the concepts and demonstrating the utility of concepts as analytical tools.

We here suggest this framework as a conceptual aid that may provide us with a handle for getting to grips with the user experience and social aspects of tangible interaction. To verify its utility, this framework needs be applied to a wider variety of cases in analysis and design, explored, expanded, probed, refined and augmented with e.g. heuristics for selecting guidelines out of the framework's second layer. This provides directions for future research.

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