

A Materials Perspective on Human-Computer Interaction

Case Studies on Tangible, Gestural, and Ephemeral User Interfaces

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Dissertation

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Abstract

Up until now, materiality has largely not been in the focus of computing and human-computer interaction (HCI), although it shapes to an increasing degree what we interact with and how we interact, especially in fields such as tangible user interfaces (TUIs) and embodied interaction. While certain aspects such as using the shape of objects for interaction have been discussed within tangible interaction design, the meaning of material qualities for TUIs has not yet been explored and investigated sufficiently. Moreover, new physical-digital types of materials as well as new material-centered application fields such as personal fabrication arise that demand for novel terminology, approaches and design knowledge. These developments lead to the situation that HCI as a discipline needs to better understand how materials shape interactions on a micro and a macro level and how this knowledge can be applied in order to design appropriate, engaging and meaningful interactions. This thesis contributes to the evolving body of works on materiality and HCI by providing a survey, a theoretical research contribution, as well as artifact and empirical research contributions.

One contribution of this thesis consists in presenting, discussing and extending *eight evolving themes on materiality and HCI* that encompass different material concepts and together form “a materials perspective on HCI” as a field of research. Furthermore, it presents a *theoretical framework* to understand and inspire how material aspects shape interaction. We explored selected material aspects presented as part of this framework in *five case studies on gestural, tangible and ephemeral user interfaces*.

Two of these case studies address *gestural interaction with physical artifacts*. In these studies, we built prototypes and developed as well as evaluated novel gesture sets. Two dominant ways how materiality shapes gestural interaction were applied: first, directly, by the materials of the artifacts used for the interaction and second, indirectly, in the way the developed gestures were inspired by manipulations of physical objects.

In two further case studies, we focus on *tangible user interfaces*. One is dedicated to the concept, design and evaluation of an end-user toolkit that allows users to design and customize devices by physical composition. This means, users can select and integrate arbitrary materials for the shell of the device and the control elements and simply link these to functions. The end-user toolkit builds a platform that conceptually enables aspects of sustainable interaction design and explores material aspects of DIY toolkits. In the other case study, we compared the use of a physical tool to a digital tool in a tabletop-based collaborative game. Analyzing the results from a materials perspective that takes the performative roles of materials into account, our study indicated that the physical tool facilitated group awareness to a greater extent than the digital tool.

A further contribution of this thesis lies in the definition, analysis, and exploration of *ephemeral user interfaces* as a novel user interface concept and field for research. Ephemeral user interfaces contain at least one user interface element that is intentionally created to last for a limited time only and typically incorporate materials that evoke a rich and multisensory perception, such as water, fire, soap bubbles, or plants. Based on a review of existing user interfaces we created a design space for ephemeral user interfaces. Our design space reveals a number of insights how material aspects shape interactions on a micro and a macro level and extends the material canon typically used for user interfaces. Additionally, we conducted an in-depth exploration of soap bubbles for interaction, studying material-based interaction constraints and material-driven user engagement.

As a whole, the prototypes and the empirical work of this thesis exemplarily reveal how material aspects matter for gestural, tangible and ephemeral interaction on different levels. They demonstrate that it is valuable to widen and rethink the canon of typical materials used for interaction in order to design appropriate, engaging and meaningful interactions. Furthermore, the work provides structured approaches revealing how materiality can get more attention in the design and analysis of human-computer interaction.

Zusammenfassung

Obwohl physische Materialien eine zunehmende Rolle bei der Mensch-Computer-Interaktion (MCI), insbesondere in Feldern wie Tangible User Interfaces (TUIs) und Embodied Interaction, spielen, ist Materialität bisher weitgehend nicht im Blickfeld von Informatik und MCI. Während gewisse Aspekte, wie etwa die Verwendung der Form von Objekten für die Interaktion, im Tangible Interaction Design behandelt worden sind, wurde die Bedeutung von Materialqualitäten für TUIs bislang nicht ausreichend untersucht. Zudem entstehen derzeit neue physisch-digitale Arten von Materialien und neue materialzentrierte Anwendungsfelder wie etwa Personal Fabrication, die neue Terminologie, neue Ansätze und neues Designwissen erforderlich machen. Diese Entwicklungen führen zu der Situation, dass die MCI als Disziplin besser verstehen muss, wie Materialien Interaktionen sowohl auf Mikro- als auch auf Makroebene beeinflussen und wie dieses Wissen angewendet werden kann, um angemessene, motivierende und bedeutungsvolle Interaktionen zu gestalten. Zum sich derzeit entwickelnden Gebiet zu Materialität und MCI leistet diese Arbeit eine Reihe von Forschungsbeiträgen. Hierzu zählen ein Survey über das Fachgebiet, ein theoretisches Framework sowie Artefakt- und empirische Beiträge.

Ein Beitrag der Arbeit besteht in der Präsentation, Diskussion und Erweiterung von *acht Themen zu Materialität und MCI*, denen verschiedene Materialkonzepte zugrundeliegen und die zusammen die „Materialperspektive auf Mensch-Computer-Interaktion“ als Forschungsfeld ausprägen. Außerdem stellt die Arbeit ein *theoretisches Framework* vor, das zur Inspiration und Analyse der verschiedenen Ebenen dient, auf denen Materialaspekte die Mensch-Computer-Interaktion gestalten können. Ausgewählte Materialaspekte, die im Rahmen des Frameworks präsentiert werden, werden von uns in *fünf Fallstudien zu Gestenbasierten, Tangible und Ephemeren User Interfaces* untersucht.

Zwei der Fallstudien untersuchen *Gesteninteraktion mit physischen Artefakten*. In diesen Studien wurden Prototypen umgesetzt und neue Gestensätze entwickelt sowie evaluiert. Zwei dominante Strategien, wie Materialität Gesteninteraktion gestaltet, wurden angewendet: erstens direkt durch die Materialien der Artefakte, die für die Interaktion verwendet wurden, und zweitens indirekt dadurch, wie die entwickelten Gesten durch die Manipulation physischer Objekte inspiriert wurden.

In zwei weiteren Fallstudien wurden Materialaspekte von *Tangible User Interfaces* behandelt. Im Rahmen der ersten Studie wurde ein Endnutzer-Toolkit konzipiert, umgesetzt und evaluiert, das Nutzern ermöglicht, sich eigene Geräte zu gestalten und individuell anzupassen, ohne dass hierfür Verdrahtung nötig ist. Nutzer können frei wählbare Materialien für das User Interface einsetzen und diese einfach mit Funktionen verknüpfen. Das Endnutzer-Toolkit bildet eine Plattform, die

konzeptuell Aspekte des nachhaltigen Interaktionsdesign umsetzt und Materialaspekte von DIY-Toolkits exploriert. In der anderen Fallstudie haben wir die Verwendung eines physischen Werkzeugs mit der eines digitalen Werkzeugs im Rahmen eines tischbasierten kollaborativen Spiels untersucht. Die Analyse der Ergebnisse aus einer Materialperspektive, die performative Rollen von Materialien berücksichtigt, hat gezeigt, dass das physische Werkzeug das Gruppenbewusstsein (Group Awareness) besser fördert als das digitale Werkzeug.

Ein weiterer Forschungsbeitrag dieser Arbeit liegt in der Definition, Analyse und Exploration von Ephemeren User Interfaces als ein neues User Interface Konzept und Forschungsfeld. Ephemere User Interfaces enthalten mindestens ein User Interface Element, das absichtlich so gestaltet wurde, dass es nur eine begrenzte Zeit hält. Typischerweise enthält es Materialien, die multisensorische Wahrnehmung evozieren, wie etwa Wasser, Feuer, Seifenblasen oder Pflanzen. Basierend auf einer Untersuchung existierender User Interfaces haben wir einen Design Space für Ephemere User Interfaces entwickelt. Dieser Design Space macht eine Reihe von Ansätzen deutlich, wie Materialaspekte Interaktionen auf einer Mikroebene und einer Makroebene gestalten, und erweitert den typischen Materialkanon für User Interfaces. Außerdem haben wir eine tiefgehende Untersuchung von Seifenblasen als Interaktionsmaterial durchgeführt, in der wir materialbasierte Constraints und materialgetriebenes Benutzerengagement untersucht haben.

Insgesamt zeigen die Prototypen und die empirischen Untersuchungen dieser Arbeit beispielhaft, wie Materialaspekte für Gestenbasierte, Tangible und Ephemere User Interfaces auf verschiedenen Ebenen von Bedeutung sind. Sie demonstrieren, dass der Kanon der typischen Materialien für die Interaktion erweitert und überdacht werden sollte, um angemessene, motivierende und bedeutungsvolle Interaktionen zu gestalten. Außerdem bietet die Arbeit strukturierte Ansätze dazu, wie Materialität bei der Gestaltung und der Analyse von Mensch-Computer-Interaktion mehr Aufmerksamkeit erhalten kann.

Preface

My personal interest in conducting research on materiality started back many years ago when I studied art history as a minor subject (next to my major subject computer science). It was during these studies when I first learned about how contemporary artists used materials as carriers of meaning beyond the media of form and how it mattered to understand the diverse material aspects to grasp the meaning of artworks. The method of material iconography focuses on this. Then, years later, I attended one of the first public demonstrations of the reactable tangible music interface during Ars Electronica in Linz, which immediately convinced me to work on tangible user interfaces, combining physical materials and digital technology. Throughout my work in this area I found that material aspects, although undoubtedly in the focus of field, yet had not been investigated and explored systematically and sufficiently.

Submitting a thesis about materiality and human-computer interaction (HCI) to a computer science department might challenge the conventional scope of topics. The aims to blaze novel trails and to bring together different disciplines and shape new research directions are often more difficult and more risky than to follow the well-trodden paths. But it is fruitful and, I would argue, also necessary in order to face the challenges of the fast evolving field of human-computer interaction that expands into all aspects of our lives. And, overall, during the last years, a body of work has evolved that deals with materiality and HCI.

This thesis is a thesis by publication and much of the work has been conducted together with colleagues who are co-authors of the included publications. Whenever I report on the work conducted together with others I use “we” in the thesis. However, whenever I am the only author of the particular work, I use “I”, which leads to the situation that “I” and “we” is both used in the text, but, hopefully, this provides more clarity than the editorial “we” would.

Over the years, many people have directly or indirectly contributed to this work. First of all, I would like to thank my supervisor Albrecht Schmidt for letting me become part of his team at the University of Duisburg-Essen, for supporting my work and for all his advice and feedback. Thanks for all the inspirations, for sharing insights about how teaching and the academic world works, for sending me to numerous conferences and workshops and for introducing me to so many outstanding HCI researchers! My special thanks go to Rainer Malaka, my co-supervisor, for hiring me at the University of Bremen when I wanted to go back to Northern Germany. I am thankful for the very supportive and trustful work atmosphere in his group, the great team, and the freedom and independence we get within our research. Thank you for your feedback and advice and for supporting me and my work! I would also like to thank Daniela Petrelli for joining the thesis committee and being an external reviewer.

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Finally, I would like to thank my friends and family. I am very grateful to my friends for being there for me, particularly to Telse Rüter und Dirk Bade for being great listeners and for sharing Ph.D. related experiences, after all. My parents-in-law, Ingo and Heike Sylvester, did a terrific job in caring for my son Lio whenever I had to work long hours, especially during the last intense weeks of writing. Thank you for your commitment! Thanks to my sister Maike Bode and her husband Robert Bode for their interest and encouragement. I am particularly grateful to my parents, Burckhard and Regina Döring, for their endless support, their confidence, their encouragement, their patience, and love. Furthermore, I would like to thank my son Lio for being there and changing my life. Keep your curiosity and positive attitude! And above all, my deepest gratitude goes to my partner, Axel Sylvester, who closely accompanied this project during the years, also worked together with me, and always came up with creative, innovative, and often unconventional ideas. Thank you for all your support and love! Without this, this work would not have been possible.

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Part I.
The Thesis

1. Introduction

Looking back at the history of computing, the physical materials used to shape the interaction with devices have been widely neglected for decades. Materials merely formed necessary casings for computing technology, often in the appearance of grey plastic. In the 1980s, at a time when the main focus was put on software, an interest in hardware ergonomics within a just starting discipline of human-computer interaction (HCI) arose as a first interest in involved materials, focusing on measurements like table height or distance to the screen, for example. While computers already had become devices for personal use, they started to be ready for mobile and ubiquitous use in the 1990s, which came along with novel form factors and materials. Yet, computer scientists still did not put much focus on materials beyond the functional hardware parts. The main efforts were in the development of software for the existing devices, which still could be overlooked in terms of variety. This changed in the beginning of this century, when device diversity exploded and computing technology got increasingly integrated into our surrounding in numerous forms and as tools and media for a growing diversity of domains. New research fields such as tangible user interfaces (TUIs) arose. Today, we as interaction designers face a huge and ever growing variety of options to design input and output in human-computer interaction. Due to many available ready-to-use hardware devices in different sizes and especially numerous sensors and actuators that allow, amongst others, unlimited forms of tangible and embodied interaction, we also see a growing need as well as potential for integrating a diversity of materials – let them be traditional, unusual or novel – into user interfaces (UIs). Materials increasingly impact user interfaces in functional or experiential ways.

To cope with this diversity of design choices and to fully leverage the potentials of materials for interaction, there is a growing need for an HCI-specific dedication to materials for interaction beyond classical hardware parts, which has been started to be addressed by the research community in recent years.¹ This was at a time when I had already started to work on a materials perspective on HCI, which had evolved out of my experience with tangible user interfaces. This thesis contributes to this body of work by presenting and discussing major material-centered themes for HCI as well as by addressing and investigating dedicated aspects of the materials for and the materiality of interaction in a number of case studies that explore tangible and embodied interaction. The research contributions² of this thesis provide new knowledge of four different

¹E.g., with key events and publications such as a CHI 2012 Workshop on materials and materiality in HCI (Rosner et al. 2012), a CHI 2012 panel on material interactions (Wiberg et al. 2013) and two special issues in the “Personal and Ubiquitous Computing” Journal, one on material computing (Buechley and Coelho 2011) and one on material interactions (Wiberg et al. 2014).

²For an overview on typical types of research contributions in human-computer interaction see (Wobbrock and Kientz 2016).

kinds: first, a *survey* of themes forming a materials perspective on HCI, second *theory*, including a material-centered terminology and framework and the definition of and design space for ephemeral user interfaces, *artifact contributions*, including a novel toolkit approach and tangible and gestural user interfaces that all contain self-constructed hardware parts next to self-developed software, and *empirical research contributions* that have led to design implications for tangible, gestural and ephemeral user interfaces in different application contexts, including gesture sets and recommendations regarding the selection of material types for interaction. In the remaining part of this introduction chapter, I first give a motivation for a materials perspective on HCI. Following, I present the research contributions of this thesis, discuss the underlying methodology of the dissertation project, and, finally, I give an overview of the thesis structure and the associated publications.

1.1. Motivation for a Materials Perspective on HCI

Computing systems in general and user interfaces in particular can neither be fully understood nor consciously designed without acknowledging the importance of physical materials. Even concepts such as information, media, or bits only exist because they are stored, processed and represented by materials (Dourish and Mazmanian 2011, Blanchette 2011, Buechley and Coelho 2011). While the dominating view in computational thinking (Wing 2006) still widely neglects materiality, researchers have started to address material-related aspects of computing, amongst others building upon social science and anthropology, to analyze information practices and cultures that emerge from material forms of information (Dourish and Mazmanian 2011, Blanchette 2011, Odom et al. 2009). For the field of human-computer interaction, it is increasingly important to understand, develop and apply design knowledge about materials for interaction and the “materiality of interaction” (Wiberg 2016). Due to the complex nature of the manifold aspects related to materials and materiality in HCI, this comes along with numerous approaches, material understandings and material-related themes. There are a number of reasons why it is timely and important to systematically address the role of materials and materiality in HCI and to cultivate a materials perspective on HCI. Among these are (1.) *Interweaving of the digital and physical in ubiquitous computing*, (2.) *the increased attention in HCI to hedonic aspects of user interfaces beyond usability*, (3.) *opportunities for novel kinds of multisensory interaction*, (4.) *potentials of novel and smart materials*, (5.) *a focus on materiality across disciplines*, and (6.) *sustainability as topic in interaction design*.

Interweaving the Digital and Physical. First of all, computing has become ubiquitous and increasingly gets embedded into our surrounding (Weiser 1991). This means, *computing power gets increasingly interweaved with physical materials*, taking on diverse forms and appearances, for example articulated in application fields such as *internet of things* (Atzori et al. 2010) and *cyber-physical systems* (Broy and Schmidt 2014). The research area of *tangible user interfaces* (Shaer and Hornecker 2010) – for more information see Subsection 2.2.2 – is dedicated to this combination of physical and digital compartments, and as such, could be seen as a research strand that explicitly marks a countermovement to the ongoing digitization and immaterialization trend

in computing (cf., Hornecker 2008). Nevertheless, while aspects such as the effects of shape for interaction (e.g., as part of affordances see Subsection 2.3.2) have been paid much attention within the research field, material aspects, although very central, still are widely unstudied, especially when it comes to systematical approaches beyond single design explorations. Whatever user interface an interaction designer builds, it will have material properties associated. This means, for both UI designers and users, we cannot not interact with materials when designing and performing interactions. This, of course, already applies to traditional user interfaces like keyboards (see for example Fishers analysis on consumers' perceptions of used plastics keyboards in his article "What we touch touches us", Fisher 2004), but gets even more important when material properties and meanings are specifically used to shape interaction techniques, e.g. by meaningful mappings of material manipulations to data functions. Thus, in order to properly understand and design hybrid systems, interaction designers need to develop material-focused design knowledge.

Beyond Usability. Second, an increased attention to *hedonic and experiential aspects of interaction and novel application domains* fosters material diversity and demands a material understanding on multiple levels. In HCI, the focus has shifted from supporting usability, a term that considers effectiveness, efficiency and satisfaction in a specified context of use, to the more holistic approach of *user experience* that encompasses a wide variety of perspectives and definitions and generally depicts a much broader concept considering all aspects of the end users interaction with a user interface. This general shift has also been discussed as a third wave of HCI (Bødker 2006). Since the early 2000s, HCI researcher increasingly discussed "Joy of use" (Hatscher 2001), attractiveness (Norman 2002), aesthetics (e.g., Tractinsky 1997, Boehner et al. 2008, Lim et al. 2007, Wright et al. 2008) as well as hedonic aspects (Hassenzahl et al. 2010) as important factors of user interfaces. To better address the different aspects of technology as experience, Wright and McCarthy introduced a framework of four threads of experiences: the compositional thread, the emotional thread, the sensual thread, and the spatio-temporal thread (McCarthy and Wright 2004). Hassenzahl argues for *experience design* as new design approach that "leads to products able to tell enjoyable stories through their use or consumption" and focuses on enabling experiences by starting from the "Why", "the needs and emotions involved in an activity" (Hassenzahl 2014). Based on this, the functionality (the What) and the interaction (the How) can be shaped (Hassenzahl 2014). This general shift from usability to user experience is certainly linked to the broadening of application contexts. Nowadays, the quality of interaction with computers needs to be assessed much more holistically than focusing on productivity and users' satisfaction simply because user interfaces do not primarily support productivity, but are used as entertainment, communication, health-supporting or information devices in all sorts of use contexts aiming to shape experiences. These could even justify "uncomfortable interactions" (Benford et al. 2012), or they could be as ambitious to evoke enchantment (McCarthy et al. 2006). This goes hand in hand with the shift from the computer as a tool to the computer as a medium (Warnke et al. 1997) and opens the door to new appearances of user interfaces incorporating novel and unusual materials beyond the traditional shape and material corpus (which used to be limited and mainly regarded as necessary casings rather than elements that shaped the overall user experience, see for example Atkinson's research (Atkinson 2010) on the physical design of computers). Moreover, it gives the material new opportunities to shape interactions and experiences, be it on the micro or macro level (see *the interaction material profile* in Subsection 3.2.2), be it

as functional or non-functional element of a user interface. While I agree with Hassenzahl that the overall aesthetic of the interface transcends the material (Hassenzahl 2014), I believe it is necessary and timely to explicitly address the aspects of materiality, especially material aesthetics, in relation to user experience.

Multisensory Interaction. A further reason to dedicate more attention to the materials involved in user interfaces is marked by their ability to create *rich multisensory interaction*. Although the human sensory capacities are so extensive, and although all senses matter for rich experiences, addressing the human senses beyond visual and acoustic stimuli is still rarely part of human-computer interaction (cf., Matassa et al. 2015). An overview on early (and often rather technology-focused than experience-oriented) explorations of haptic, olfactory or taste interfaces can be found in (Kortum 2008). Especially the touch sense, a very important sense that comes along with our bodies' "largest and oldest sense organs", "cannot be deceived or fooled", "educates vision" and "set[s] the boundaries of the self" (Gallace and Spence 2014, pp. 3-4) should be addressed more systematically in HCI. Surfaces, especially the currently dominating touch devices, become increasingly flat and smooth. The material diversity we are in touch with when interacting with devices and thus our haptic and tactile experiences are still very limited. Researchers write about an increasing "hunger for touch" in the society nowadays (Gallace and Spence 2014, p. 252), which even stronger demands for an increased attention to tactile and haptic stimuli in HCI. Obrist and colleagues have started to address this still underexplored design space for tactile experiences as part of user interface design by developing categories for a human-experiential vocabulary (Obrist et al. 2013) about touch. Similarly she and colleagues have dedicated research on experiences of smell and taste with implications for olfactory (Obrist et al. 2014b) and gustatory interfaces (Obrist et al. 2014a). By extending material diversity for interaction beyond traditionally used materials, we can raise potentials that materials naturally offer for multisensory experiences, especially if used beyond passive surface materials or shells as functional material for interaction. This implies that an inclusion of different materials should be part of the early interaction concept and design rather than a subsequent integration. Thus, I regard a focus on physical materials as important within the current trend to realize multisensory interaction, which is in line with the goals of natural interaction, reality-based interaction and embodied interaction, see Chapter 2.

New Materials. A fourth strand that demands for a materials perspective on HCI is the development of *novel and smart materials*. While we already have seen the general interweaving of physical objects and electronics as a trend in ubiquitous computing, this evolution will proceed on a material level leading to a fusion of physical and digital properties in single materials. Driven by the engineering discipline material science, advanced materials form one of the most innovative research fields of our time. Among the research goals are programmable materials. In simple forms (e.g., shape memory alloys) they already exist today, and some first applications with smart materials in HCI research have been explored (cf., Coelho and Zigelbaum 2011, more in Subsection 3.1.5). Hiroshi Ishii, HCI researcher in the MIT Media Lab, has formulated the vision of *radical atoms* as future trend beyond *tangible bits* (Ishii et al. 2012) that builds on these current developments in material sciences and envisions user interfaces with materials that transform by themselves. Another area of research and DIY-practice where we find a trend towards interweaving physical materials, electronics and software can be found in personal fabrication and the fab

lab movement. Neil Gershenfeld, founder of the first fab lab and one of the leading researchers in the field, argued in his fundamental book “Fab. The coming revolution on your desktop - from personal computers to personal fabrication” that “the final frontier in rapid prototyping is to introduce functional as well as structural materials, in order to print complete working systems (Gershenfeld 2005, p. 101). The idea is to use rapid prototype machines, like 3D printers, to create functional systems with all materials needed in one individual operation. An early example marks the printed robot fish by Evan Malone in 2010 at Carnegie Mellon University (Lipson and Kurman 2013, p. 273). While this overall idea, which ideally can be scaled down to nano scale, for the most part still is a vision, there are a large number of advanced materials ready to be explored by HCI researchers for interaction, especially as sensory materials (as for example done in Rendl et al. 2012) and actuary materials (as applied in Coelho and Zigelbaum 2011). Beyond the potential to integrate (programmable) behavior into materials, the overall possibility to design materials with certain properties offers a novel perspective to materials for HCI. In future, a typical UI design task might rather focus on the design and invention of a new material instead of selecting an existing one.

Focus on Materiality across Disciplines. A development that supports a materials perspective on HCI is an ongoing general *shift towards the importance of materiality as well as towards shaping and understanding materials across many other disciplines* and trans- or interdisciplinary research fields. Many of these topics around materiality are relevant for the field of human-computer interaction and have only just started to get attention within the community. Of course, in many fields like architecture and product design, both related to HCI in many aspects, the exploration of materials already has a long and ongoing tradition. Recently, the application of novel materials has been in the focus (cf., the “catalogue of materials that redefine our physical environment” Transmaterial 1-3 Brownell 2005, 2008, 2010). Beyond exemplary material studies and explorations, first works have been conducted to systematically analyze material relevance in architecture (Langenmaier 1994, Wachs 2008) and to evolve structural approaches around materials (cf., Ashby and Johnson 2010). In aesthetic theories in western culture material was regarded as inferior to idea and form for centuries (Wagner 2008, Boivin 2010). In art, material mainly had been the media of form. The materials’ history as well as their meaning in everyday contexts were basically eliminated in artworks (Wagner 2002). This changed in the 20th century, when the materials themselves became carrier of meanings (Wagner 2002). Diverse, e.g., everyday and “low” materials became part of artworks, explicitly using the materials’ connotations for their meaning. This development led to dedicated approaches like the method of material iconography that focuses on the properties and meanings of the artworks’ materials in the interpretation (Wagner 2002). A further field of material studies HCI can learn from is the anthropologic research field of “material culture” (e.g., Miller 1997, Prown 1982). Among the founding works for a dedication to the material world in social sciences is Latour’s “actor network theory” that argues for an agency of material things (Latour 2007). Latour, Miller and other scholars have significantly influenced what is called a material turn as part of the cultural turn in social and cultural studies, a novel dedication to materials and things (cf., Köhler et al. 2004, Bennett 2010, Schubert 2010), a research agenda that as well already started to cover “digital material/ism” (Reichert and Richterich 2015) – see also “digital antropology” (Horst and Miller 2012) and the material turn in game studies (Apperley and Jayemane 2012). It is time to develop a focus on materiality in HCI as well.

Sustainability. Finally, another strand of research that urges for a deeper understanding of the materiality and materials involved in user interfaces and technology-enhanced artifacts is *sustainability as a topic of HCI*. Sustainability research in computing (Knowles et al. 2013), sustainable HCI (DiSalvo et al. 2010, Goodman 2009) and sustainable interaction design (Blevis 2007) have recently been started as important research areas with a growing demand for novel solutions on a variety of aspects related to sustainability. The whole range of sustainability research in computing encompasses a number of topics like reducing carbon footprints, monitoring the state of the nature environment, foster environmentally responsible behavior, make better use of renewable resources or patterns of consumptions (Knowles et al. 2013). Putting a focus on the material world and reflecting potentials for improvement when it comes to material aspects of interactive artifacts especially brings up questions around manufacturing, use, and disposal practices (Goodman 2009). In his introduction to sustainable interaction design Blevis (2007) specifically discussed different design cases around the use, reuse, and disposal of interactive artifacts. Among these are, e.g., salvage, recycling, remanufacturing for reuse or achieving heirloom status. In order to design for sustainability, creating meaningful interactive artifacts with long use-lifetimes should be in the focus of interaction design. When Odom et al. (2009) examined users' relations to possessions and their reasons for preserving or discarding things, they found four relevant areas, namely engagement, histories, augmentation, and perceived durability that play major roles. Interestingly, e.g., traces of use, aging and patina evolving on the physical materials as well as opportunities to reuse, renew or customize led to stronger attachments of the owners to the objects. These aspects should get more attention in HCI. Overall, a dedication to sustainability ineluctably leads to a material focus.

Having pointed out several strands that suggest to put the material into focus when designing interactive systems, a materials perspective on HCI can meet the described requirements and needs by addressing different subfields. These relate to the following themes: (1.) *Conceptualizing Material in HCI*, (2.) *Material-Focused Frameworks and Methods*, (3.) *Physical Materials*, (4.) *The Computer as Material*, (5.) *Novel and Advanced Materials*, (6.) *Making, Craft and Do-it-Yourself*, (7.) *Sustainability and Interaction Design*, (8.) *Understanding the Roles of Materials in Practices*. In Section 3.1, I elaborate these in more depth and present related work in human-computer interaction (for an overview, see also Figure 3.1). The themes serve as a structure to guide material-focused research, to broaden the scope a materials perspective can take, and to frame the higher-level contributions of this thesis. The contributions of this thesis to dedicated aspects of the material themes are presented in the following section.

1.2. Research Contributions

This dissertation contributes to the evolving body of work on materiality and HCI by providing an overview over the material-related research strands in HCI, by developing conceptual foundations for materials and materiality in interaction design and by empirically exploring three user interface classes, in which materiality plays an important role for the interaction in five case studies: gestural interaction with interactive objects, tangible interaction and ephemeral user interfaces.

In all three interface classes, prototypes have been built, explored, and evaluated with users. The projects have been driven by the goal to explore, practically apply, and better understand material aspects in interaction design. The main contributions of the thesis are the following:

1. A survey of the **prevailing material themes** currently evolving in human-computer interaction.
2. **Material terminology and a material-focused framework** to support the understanding of materials in user interfaces along three aspects: the types of materials, the interaction material profile and the material representation spectrum.
3. An investigation of the role of **material aspects in gestural interaction with interactive objects**. We conducted two case studies. The first one investigates mid-air gestures with mobile phones in the context of interactive tabletops. Among the results are the design and evaluation of novel and original gesture sets for interacting with mobile devices on interactive surfaces. In the second case study we constructed a touch-enabled steering wheel and designed as well as evaluated a gesture set to perform secondary tasks, such as the control of infotainment systems, in the car during driving.
4. An **application of the material perspective on tangible user interfaces** by studying aspects materials unfold on the macro level of interaction. In the first case study, we compared the use of a physical and a digital tool in a collaborative tabletop-based game and focused on how the tools supported collaboration. In a second case study, we developed and tested a tangible end-user toolkit that was based on physical composition, incorporated typical DIY craft and personal fabrication materials, and was specifically designed for customization, renewal, and reuse.
5. A survey on 50 user interfaces incorporating ephemeral materials leading to the **definition of the term “ephemeral user interface” as a new class of interfaces** as well as a **design space for ephemeral user interfaces**. This work presents a foundation for a new research field on ephemerality as part of user interfaces and provides an original, timely and unique contribution to the material perspective on HCI by systematically extending the material scope.
6. An in-depth exploration of selected material aspects of ephemeral user interfaces focusing on **soap bubbles as material for interaction**. We developed and evaluated the soap bubble interface putting an emphasis on **the study of form of soap bubbles as raw material for interaction on micro as well as macro levels of interaction**.

In the following, I will explore these in more depth and provide references to the corresponding parts of this thesis as well as to the included publications that present these contributions. Additionally, Figure 1.1 provides an overview on the presented research contributions with related case studies, methodology, addressed material themes and publications.

1. Introduction

Research Contributions and Publications				
Topic	Research Contributions	Methodology	Related Material Themes	Publications
 <p>1. Material Themes</p>	Survey of the prevailing material themes currently evolving in human-computer interaction as part of a "materials perspective on HCI"	Systematic literature analysis	Covers all eight material themes (1-8)	1.) (Döring et al. 2009) 2.) (Döring et al. 2012a) 3.) (Döring 2014)
 <p>2. Material Terminology and Framework</p>	Classification of material types; specification of the interaction material profile and of the physicality representation spectrum	Interpretation of design artifacts and systematic literature analysis including sources from different disciplines	Conceptualizing Material in HCI (1), Material-Focused Frameworks and Methods (2)	4.) (Döring 2016a)
 <p>3. Materiality and Gestural User Interfaces</p>	Investigation of physical material aspects in gestural interaction with interactive objects; gesture sets; validation of gestures in user studies	Prototyping; three lab-based user studies that cover a variety of approaches including the assessment of quantitative and qualitative data, a gesture elicitation study, eye-tracking, and a driving simulation apparatus	Physical Materials for Interaction (3), The Computer as Material (4)	5.) (Sahami et al. 2009) 6.) (Döring et al. 2010b) 7.) (Döring et al. 2011)
 <p>4. Materiality and Tangible User Interfaces</p>	Investigation of performative roles of materials in collaborative tangible user interfaces and tangible DIY toolkits	Prototyping; construction of an end-user design toolkit; lab-based user study with a mixed methods approach including video coding for patterns in collaboration; evaluation workshop	Physical Materials for Interaction (3), Making, Craft and Do-It-Yourself (6), Sustainable Interaction Design (7), Understanding the Roles of Materials in Practices (8)	8.) (Döring et al. 2010a) 9.) (Schmidt et al. 2011) 10.) (Speelpenning et al. 2011)
 <p>5. Ephemeral User Interfaces</p>	Definition and foundation of the term "ephemeral user interface" as a new class of interfaces and presentation of a design space for ephemeral user interfaces	Systematic literature and artifact analysis	Material-Focused Frameworks and Methods (2), Physical Materials for Interaction (3), Novel and Advanced Materials (5), Sustainable Interaction Design (7)	11.) (Döring et al. 2013a) 12.) (Döring et al. 2013b)
 <p>6. The Soap Bubble Interface</p>	In-depth exploration of soap bubbles as material for interaction (on micro- and macro levels; exploration of the physicality representation spectrum)	Prototyping; field study applying an ethnographic approach; lab-based user study focusing on UX and emotional response (quantitative measurements via questionnaires and qualitative insights through observation and video analysis)	Physical Materials for Interaction (3), Novel and Advanced Materials (5)	13.) (Sylvester et al. 2010) 14.) (Döring et al. 2012) 15.) (Döring et al. 2015)

Figure 1.1.: Research contributions and publications.

1. Material Themes in HCI. An emerging materials perspective on HCI can be found in different **material themes** that currently evolve. Based on a comprehensive literature review and observed emerging trends at recent HCI conferences (e.g., ACM CHI, ACM TEI, ACM DIS, ACM Ubicomp, ACM UIST), I identified eight material themes that stem from different motivations, have different understandings about what a material is in HCI, and focus on different aspects of a materials perspective on HCI. As all shape this emerging field, I give an overview of the themes in Section 3.1. The first two themes address *material-centered theory* and work on embracing terminology and methods. Themes three to five explore materials in *material-centered practice* focusing on different material types. With making culture and sustainability themes six and seven present comprehensive fields of *material-centered fields* that both evolved outside HCI and increasingly influence the field. Although sometimes not explicitly picked out as central themes, both are characterized by a focus on materials. Last, theme eight encompasses works that address a *material-centered analysis*, looking at materials in context and focusing on macro aspects. Overall, the themes present a structure for a materials perspective on HCI that provides a novel approach to bring together different angles of materiality and to give a comprehensive overview over this field. With our own case studies we explored these themes. The following publications contribute to the material themes:

Publications

Tanja Döring, Antonio Krüger, Albrecht Schmidt, Johannes Schöning: Tangible, Embedded, and Reality-Based Interaction. In: *it - Information Technology*, Volume 51 Issue 6, 2009. De Gruyter Oldenbourg (Berlin) 2009, pp. 319-324.

Tanja Döring, Axel Sylvester, Albrecht Schmidt: Be-greifen “beyond the Surface” - Eine Materialperspektive auf Tangible User Interfaces. In: Bernard Robben, Heidi Schelhowe (Eds.): *Be-greifbare Interaktionen - Der allgegenwärtige Computer: Touchscreens, Wearables, Tangibles und Ubiquitous Computing*. Transcript (Bielefeld) 2012, pp. 115-134.

Tanja Döring: The Return of the Physical: Tangible Trends in Human-Computer Interaction. In: Günther Friesinger, Jana Herwig (Eds.): *The Art of Reverse Engineering: Open - Dissect - Rebuild*. Transcript (Bielefeld) 2014, pp. 83-96.

2. Material Terminology and Framework. A deeper understanding of material aspects in human-computer interaction requires a materials terminology for user interfaces. In Section 3.2 I provide a framework that structures material aspects in HCI along three aspects: *materiality and types of materials*, *the interaction material profile*, and *the physicality representation spectrum*. This framework supports the understanding of material aspects that unfold in human-computer interaction. While primarily intended to be helpful for analysis, it could also serve as a structure to support material concepts during design tasks in the future. My framework presents a novel and original contribution extending other existing framework approaches (e.g., Wiberg 2014, Giaccardi and Karana 2015) as it equally integrates computational and physical materials, considers different degrees of physical representations in user interfaces (from a metaphorical application

to the physical material itself), and integrates a micro and a macro level of interaction. In the context of this thesis, I apply the framework to discuss our case studies (see Chapter 4). The following publication presents *the interaction material profile*:

Publication

Tanja Döring: The Interaction Material Profile. Understanding and Inspiring How Physical Materials Shape Interaction. In: *Proceedings of the 2016 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM (New York) 2016, pp. 2446-2453.

3. Materiality and Gestural User Interfaces. Gestural interaction with physical artifacts, also called “tangible gesture interaction” (Van Den Hoven and Mazalek 2011), is a growing field of research that has yet only rarely been explicitly addressed, rather as subfields of gestural and tangible interaction (Angelini et al. 2015b). We explored gestural interaction with physical artifacts from a materials perspective and conducted two case studies with distinct settings, in which we designed and evaluated gesture sets (see Section 4.1). The first case study is dedicated to mid-air gesture interaction with mobile phones in the context of tabletop applications and presents one of the early works combining the mobile phone as private device with a tabletop as collaborative platform via gestural interaction (see Subsection 4.1.1). We explored a number of different applications (e.g., an interactive cafe table, a presentation tool, board games) and combined the designed gestures to one gesture set. These resulting gestures all take advantage of the existing setting with mobile phone as private device and the tabletop as collaborative device, e.g. by supporting the exchange of data between the devices via gestural interaction. We explored one of the applications – an interactive poker game – in more depth, conducted an evaluation, and analyzed how aspects of materiality shaped the gestural interaction. The second case study deals with gestural interaction in the automotive context (see Subsection 4.1.2). We constructed a multi-touch steering wheel and conducted a gesture elicitation study (Wobbrock et al. 2009) in order to identify a suitable gesture set for controlling a navigation system and a music player as secondary tasks during driving. The study presents the first user-defined gesture set for multi-touch interaction on the steering wheel. In a subsequent study, we evaluated the gesture set in terms of driving distraction in a driving simulating environment with integrated eye tracking technology and found that the drivers’ visual demand is reduced significantly when performing gestures compared to using conventional infotainment systems. In both explorations of gestural interaction with physical artifacts we found two ways how materiality shapes the interaction: first of all by the materials of the artifacts, the mobile phone and the steering wheel, especially regarding functionality, affordances and constraints, and second, in the way the gestures were inspired by manipulations of physical objects. Section 4.4 discusses these aspects in further depth. The following publications present the results on materiality and gestural user interfaces:

Publications

Alireza Sahami Shirazi, Tanja Döring, Pouyan Parvahan, Bernd Ahrens, Albrecht Schmidt: Poker Surface: Combining a Multi-Touch Table and Mobile Phones in Interactive Card Games. In: *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI'09)*. ACM 2009, Article No. 73 (2 Pages).

Tanja Döring, Alireza Sahami Shirazi, Albrecht Schmidt: Exploring Gesture-Based Interaction Techniques in Multi-Display Environments with Mobile Phones and a Multi-Touch Table. In: *Proceedings of PPD 10: Workshop on Coupled Display Visual Interfaces (in Conjunction with the International Conference on Advanced Visual Interfaces AVI 2010)*, pp. 47-50.

Tanja Döring, Dagmar Kern, Paul Marshall, Max Pfeiffer, Johannes Schöning, Volker Gruhn, Albrecht Schmidt: Gestural Interaction on the Steering Wheel - Reducing the Visual Demand. In: *Proceedings of the 2011 SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM 2011, pp. 483-492.

4. Materiality and Tangible User Interfaces. Material representations of digital data, which could be, e.g., static or dynamic digital media, digital attributes, computational operations, or data structures (Ullmer and Ishii 2000) are the central idea of tangible user interfaces. But although the field exists for a while already, many aspects of materiality have not been explored in depth, e.g. material affordances beyond shape, (cf., Baskinger and Gross 2010). A materials perspective on tangible user interfaces can gain insights about many aspects including how materials shape the interactions on micro and macro levels. While we focused on the micro level of interaction in our case studies on gestural interaction, we explore selected aspects of macro interaction in our case studies on tangible user interfaces (see Section 4.2). The first case study is dedicated to the concept, design and evaluation of an end-user toolkit that is based on the simple composition of physical materials and does not require any wiring, programming, or understanding of the electronic circuitry (see Subsection 4.2.1). Furthermore, it allows the user to design and customize his or her own device by selecting and integrating arbitrary materials for the shell of the device and the control elements. The end-user toolkit, which was evaluated as toolkit to design an alarm clock in a design workshop, builds a platform that conceptually enables aspects of sustainable interaction design, e.g., customization, renewal, and reuse (cf., Blevis 2007) and explores material aspects of DIY toolkits, contributing to the material theme of *Making, Craft and Do-It-Yourself*. In the second case study we compared the collaborative use of a physical to a digital tool in a tabletop-based game (see Subsection 4.2.2). Understanding the different effects of physical and digital representations of data is an important research focus of the TEI research community, especially in the context of tabletop applications (Hancock et al. 2009, Lucchi et al. 2010, Tud-denham et al. 2010). Our study addressed this focus by studying the different uses of a wooden and a graphically represented magnifier glass as tools in a digital board game on the tabletop surface. Analyzing the results from a materials perspective that takes materials performative roles into account (Fuchsberger et al. 2013, Giaccardi and Karana 2015), our study indicated that the

physical tool facilitated group awareness to a greater extent than the digital tool. The following publications present the results on materiality and tangible user interfaces:

Publications

Tanja Döring, Bastian Pfleging, Christian Kray, Albrecht Schmidt: Design by Physical Composition for Complex Tangible User Interfaces. In: *Proceedings of the 2010 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM (New York) 2010, pp. 3541-3546.

Albrecht Schmidt, Tanja Döring, Axel Sylvester: Changing How We Make and Deliver Smart Devices: When Can I Print Out My New Phone? In: *IEEE Pervasive Computing*, 10(4), IEEE (New York) 2011, pp. 6-9.

Tess Speelpenning, Alissa Antle, Tanja Döring, Elise van den Hoven: Exploring How Tangible Tools Enable Collaboration in a Multi-Touch Tabletop Game. In: *Human-Computer Interaction – INTERACT 2011: 13th IFIP TC 13 International Conference, Volume 6947 of the Series Lecture Notes in Computer Science*. Springer (Berlin Heidelberg) 2011, pp. 605-621.

5. Ephemeral User Interfaces. In our work, we have introduced, defined and explored *ephemeral user interfaces* as a novel UI concept and field for research (see Section 4.3.1). Ephemeral user interfaces contain at least one user interface element that is intentionally created to last for a limited time only and typically incorporate materials that evoke a rich and multisensory perception, such as water, fire, soap bubbles or plants. While this type of interface has been prototyped and presented in many scientific, artistic and DIY contexts, so far there has not been a common understanding and denotation for them. Based on a review of 50 existing user interfaces that fall into this research area but have not been discussed under one common term before, we created a design space for ephemeral user interfaces providing a terminology for (a) *materials for ephemeral UI elements*, (b) *interaction* and (c) *aspects of ephemerality*. Our design space reveals many interesting and novel insights how material aspects can shape interactions on micro and macro levels and extends the material canon typically used for user interfaces. These presented dimensions as part of the design space provide a structure to analyze and explore ephemeral user interfaces from a materials perspective. It systematically extends the materials scope conventionally applied for user interfaces and, moreover, it reveals opportunities for future research into different novel directions. Among these are, for example, design tools for material-focused user interfaces, ephemeral smart materials, and nature and ephemerality as metaphor for hard- and software design. Especially this last aspect takes the degree of physicality representation in user interfaces into account and applies the concept of ephemerality to computational materials as a further aspect. With this work, we set a foundation for this research area by shaping and defining the term *ephemeral user interface*, by establishing a collection of ephemeral UIs³ and by conducting a survey leading to a design space for ephemeral user interfaces. Additionally, we practically

³The collection of ephemeral user interfaces, structured by dominating interaction materials, is currently established on www.ephemeral-UIs.org.

explored aspects of ephemeral user interfaces in a case study, in which we created, presented and studied a user interface that uses soap bubbles for interaction, which presents another research contribution of this thesis. The following publications present the definition and design space for ephemeral user interfaces:

Publications

Tanja Döring, Axel Sylvester, Albrecht Schmidt: A Design Space for Ephemeral User Interfaces. In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. ACM (New York) 2013, pp. 75-83.

Tanja Döring, Axel Sylvester, Albrecht Schmidt: Ephemeral User Interfaces: Exploring the Aesthetics of Interface Components that Do Not Last. In: *ACM Interactions*, Volume 20 Issue 4, July + August 2013. ACM (New York) 2013, pp. 32-37.

6. The Soap Bubble Interface. To practically explore material aspects of ephemeral user interfaces we designed, constructed, presented and evaluated the soap bubble interface (see Subsection 4.3.2), an interactive installation using soap bubbles for interaction. In this case study, we studied and analyzed soap bubbles as unconventional and ephemeral interaction material in detail, including many aspects on the micro and the macro level of interaction. While other prototypes and media installations have used soap bubbles for output before (e.g., Jauk and Ranzenbacher 2005), we focused on soap bubbles for input, which leads to interesting and diverse interaction techniques that are directly influenced and guided by the material and its properties. We used the soap bubble interface for two different applications: a light-and-sound interaction and an interactive game in a number of different settings (an open gallery event, a party, demo sessions at two conferences and in a lab-based user study), gathering experiences from in total more than 100 users interacting with the installation. Focusing on novel concepts such as material-based interaction constraints and material-driven user engagement, our case study revealed that a materials perspective on interaction can lead to novel interaction techniques and shape novel experiences. Furthermore, we assessed the emotional experience of soap bubbles as input material for an interactive game and compared it to plastic spheres as input in a lab-based user study. We found that both, real soap bubbles and plastic spheres, were suited for interaction and evoked a high user experience as well as positive emotions. The real soap bubbles additionally provoked a high affect regarding surprise. After all, although the soap bubble interface demonstrates an unusual interaction, we believe that the applied concepts are transferable and inspire future work on materials and HCI. It provides an exemplary case study for an in-depth exploration of an unusual interaction material that extends the scope of materials for user interfaces und delivers insights that can be transferred to other materials, be they computational or physical. The following publications present the Soap Bubble Interface and related results:

Publications

Axel Sylvester, Tanja Döring, Albrecht Schmidt: Liquids, Smoke, and Soap Bubbles: Reflections on Materials for Ephemeral User Interfaces. In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM (New York) 2010, pp. 269-270.

Tanja Döring, Axel Sylvester, Albrecht Schmidt: Exploring Material-Centered Design Concepts for Tangible Interaction. In: *Proceedings of the 2012 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM (New York) 2012, pp. 1523-1528.

Tanja Döring, Franziska Lorz, Rainer Malaka: Assessing the Emotional Experience of Soap Bubbles as Input Material for Interactive Games. In: Anette Weisbecker, Michael Burmester, Albrecht Schmidt (Eds.): *Mensch und Computer 2015 - Workshopband*, De Gruyter Oldenbourg (Berlin) 2015, pp. 559-566.

1.3. Methodology

The subject and methodological scope of this thesis is grounded in the interdisciplinary research field of human-computer interaction. Being a discipline with a relatively young history, HCI has integrated and applied methods as well as domain knowledge from many different disciplines like engineering, psychology, sociology, art and design, just to name a few. Due to the field's broad scope and complex nature encompassing understanding and designing for humans' needs, constructing novel technology artifacts and putting them into application contexts as well as gathering and analyzing quantitative and qualitative aspects of interaction, HCI researchers need to apply and adapt methods from diverse disciplines. Furthermore, because of advancing technology, new forms of computational artifacts and related use scenarios, the themes of HCI are ever-changing and with them the repertoire of methods.

This thesis contributes to the currently evolving field around materiality in HCI. This topic demands, beyond the interdisciplinarity regarding methods and domain knowledge applied in human-computer interaction, a transdisciplinary approach. This means, in order to shape and structure a materials perspective on HCI, a variety of domains that focus on diverse materials aspects (e.g., materials science, product design, architecture or art) need to be considered and included, resulting in a novel sub-field with its own themes, theories and methods.

Methodically, this work encompasses a wide variety of research methods including qualitative and quantitative. As part of the foundations for a materials perspective on HCI the thesis provides a *survey contribution* about material themes in HCI (see Section 3.1). Second, it contributes to *theory* by a material-focused framework to discuss material aspects of user interfaces (see Section 3.2) and, as part of the foundations for ephemeral user interfaces, by giving a definition of

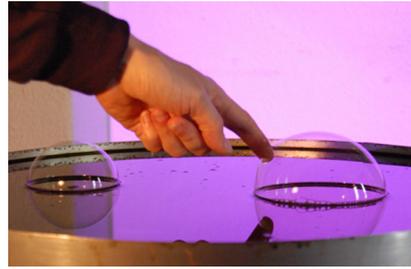
ephemeral user interfaces as well as by surveying ephemeral user interfaces and constructing a design space (see Section 4.3). These outcomes of the thesis are methodically based on qualitative data analysis (cf., Lazar et al. 2010, p. 280 ff.), including literature and artifact analysis, partly based on using grounded theory as a method for rigorously reviewing literature (Wolfswinkel et al. 2013). Third, the outcome of the thesis includes a number of *artifact contributions*, research prototypes, that provide means to experience novel interactions as well as practically and exemplarily explore dedicated research questions. E.g., the prototype for our toolkit approach as part of case study #4 explores an original approach of separating the user interface components from the application logic for tangible user interfaces. All prototypes that were built for this thesis research contained self-developed hardware and software parts. I co-developed and co-constructed the interactive tabletop and mobile phone-based prototypes used in the case study of mobile phone gestures, the multi-touch steering wheel, the toolkit by physical composition and the soap bubble interface. Figure 1.2 provides an overview on the five research prototypes that we used in our experimental research to derive generalizable design implications based on empirical work to these kind of user interfaces as part of *empirical research contributions*, the fourth contribution type of this thesis. We dedicated a case study to each prototype and conducted one or two evaluation(s) in each case study.

In case study #1, gesture-based mobile phone interaction with interactive tabletops, we conducted a user study (N=21) in which we tested and compared how players liked to play a poker game in two conditions, a multi-touch version without mobile devices and a version with gesture-based mobile phone interaction. In the study, which was conducted as within group design experiment, groups of three played each game version for about 15 minutes. After each condition, we gathered each users' assessments regarding the ease of interaction techniques and how much they liked them with a self-designed questionnaire combining Likert scale items and open commentary areas.

In case study #2, focusing on gestural interaction on the steering wheel, we conducted two user studies. In the first study (N=12), we elicited a user-defined gesture set for 20 commands by applying the method to derive user-defined gesture sets introduced by Wobbrock et al. (Wobbrock et al. 2009) to the automotive context. This method is based on earlier work on user elicitation studies (Nielsen et al. 2003) and addresses a procedure to gather users' ideas for gestural surface interaction by first demonstrating the effect of a certain command and then collecting the user's gesture. Finally, the collected gestures are grouped by agreement for each command. Based on the most frequent gestures, a consistent gesture set for all commands is identified, which normally demands adjustments by the experimenters. With the gesture set we derived in our first user study we conducted a second user study, in which we compared a subset of the steering wheel gesture set to interaction with conventional devices (radio and navigation system located at the middle console) during driving in a driving simulation setup. The study was conducted as within subject design (N=12), so that each participant drove two trials with one run of a fixed duration in each condition we had. As test apparatus, we used a standardized driving simulation – the Lane Change Test (Mattes and Hallen 2008) – and integrated an eye tracker to record the driver's eye gaze. As dependent variables we assessed (1) the number of actions performed in each run, (2) the driving performance data, and (3) data on visual demand: (a) number and (b)



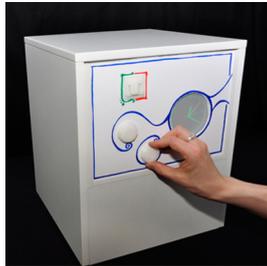
(a) Prototype case study # 1: Poker surface. Gestural interaction with mobile phones at an interactive tabletop.



(b) Prototype case study # 5: The soap bubble interface. Using soap bubbles as ephemeral interaction material.



(c) Prototype case study # 2: Multitouch steering wheel. Gestural interaction as secondary task during driving.



(d) Prototype case study # 3: End-user design by physical composition.



(e) Prototype case study # 4: Futura. Comparing multitouch and tangible interaction at an interactive tabletop.

Figure 1.2.: The five research prototypes that we used in our experimental research to derive generalizable design implications. I co-designed and co-built poker surface, the soap bubble interface, the multi-touch steering wheel and the end-user toolkit.

duration of users' glances at the interface. The data gathered in the study was analyzed with means of descriptive and inference statistics.

In case study #3, addressing end-user design by physical composition, the developed toolkit to build an alarm clock with physical user interface was evaluated within a half-day design workshop with potential end users as well as designers (N=15). In this workshop we compared our toolkit approach to pure paper-based prototyping (within group design) and collected quantitative data via questionnaires as well as qualitative data by observing the participants and analyzing the resulting workshop artifacts. As a questionnaire we used a reduced version of the USE questionnaire (Lund 2001) that addresses classical usability aspects like usefulness, ease of use, ease of learning, and satisfaction.

In case study #4, which compared a tangible and a digital tool for collaboration in a tabletop game (N=45, groups of three, within group design), we combined quantitative and qualitative methods.

Quantitative measures included game performance and scores, as well as tool use (occurrence and temporal patterns of usage). In the self-designed questionnaire, we asked about learning outcomes, collaboration and tools use and used open-ended as well as closed questions (7 point Likert scale rating). Additionally, we took structured observational notes (focusing on how the players interacted and how they used the tools) and collected videos of the session, which were later on analyzed for patterns in collaboration by three researchers. These patterns were created by analyzing our observational notes and the videos starting from underlying theoretical concepts. We considered verbal interactions including utterances, discussion, information exchange, negotiation, and suggestions, and physical interactions including gesturing and performing actions on game objects. The resulting data was statistically analyzed.

Finally, in case study #5, the soap bubble interface, we conducted two user studies: one over six different public and semi-public settings each lasting from 3 to 7 hours with more than hundred users in total and one in the lab (N=10). While we collected qualitative data about how users approached and used the soap bubble interface in the first one, the second study was a controlled experiment that primarily focused on quantitative data about the users' emotional responses after using the interface and additionally allowed qualitative insights through observations and video analysis. In our first study, we selected an ethnographic approach and observed people using the soap bubble interface in settings like a public street art festival and a party. Within our observations, we focused on material-centered interaction concepts: (1) material-based interaction constraints and (2) material-driven user engagement and took notes as well as collected videos of the interactions. Our second study compared using the soap bubble interface with real soap bubbles versus a setup with transparent plastic half spheres as input devices for a game regarding user experience and emotional response as well as differences in the way people interacted (within group design). As quantitative measurements we employed the user experience questionnaire (UEQ) (Laugwitz et al. 2008), which addresses the usability and UX aspects attractiveness, design quality, and use quality with a list of attribute pairs that need to be rated on a 7 point Likert scale. Additionally, we used the PANAS-X questionnaire (Watson and Clark 1999) that assesses positive and negative affect and offers a number of further modules dedicated to emotions, from which we selected the modules for the affective states fatigue, surprise and serenity. The questionnaire consists of a list of attributes describing emotional states which the participant has to rate on a 5 point Likert scale. To collect qualitative data on general interaction differences we took observational notes and collected videos of all sessions. The resulting data was statistically analyzed.

So overall, next to the literature and artifact analysis work, we conducted in total seven user studies within our five use cases combining a broad range of qualitative and quantitative methods. These encompass controlled lab experiments addressing usability and user experience aspects or driving distraction and visual demand including measuring eye movement with eye tracking, a gesture elicitation study, a half-day design workshop in groups, mixed method approaches combining questionnaires, user observation and video coding as well as ethnographical work in public contexts. Where applicable, we conducted statistical analyses using descriptive and inference statistics.

1.4. Thesis Outline

This doctoral dissertation by publication is divided into two parts. Part I presents the motivation, background and conceptual foundations of “a materials perspective on human-computer interaction”, introduces the conducted surveys and case studies exploring the materials perspective and structures as well as discusses the contributions. It is structured as follows. This introduction is followed by an explanation of *fundamental terminology, interfaces and concepts of human-computer interaction beyond the desktop* in Chapter 2, focusing on relevant aspects for the scope of this thesis. Chapter 3 then addresses the materials perspective on HCI by structuring the problem space from two angles. First, in Section 3.1, I explain *eight themes of a materials perspective on HCI* that were identified through extensive literature reviews and conference interactions. These themes serve as a structure to understand the different aspects of this emerging research field on materiality and at the same time provide an overview over related work of this thesis. Second, in Section 3.2, I provide a *framework and terminology* to discuss material aspects of user interfaces, focusing on the *types of materials, the interaction material profile, and the physicality representation spectrum*. The results presented in Chapter 3 are then applied in Chapter 4 to frame and discuss selected materials aspects that we explored in our case studies and surveys. Chapter 4 presents these case studies and surveys structured into three sections that are each dedicated to a type of user interface explored in this dissertation: *materiality and gestural user interfaces* 4.1, *materiality and tangible user interfaces* 4.2 and *materiality and ephemeral user interfaces* 4.3. Each section gives a summary of the related research projects and ends with a discussion of the results from a materials perspective. Finally, at the end of part I, Chapter 5 presents a *conclusion* of this thesis’ research contributions, including a summary and a discussion of opportunities for future work.

Part II consists of 15 publications, presented in their original format as published. These publications cover a broad variety of academic publication formats including three full papers on international conferences, three journal contributions, two book chapters, four work-in-progress/late-breaking-work publications, one demo presentation, and two workshop publications. Within this thesis, the publications are thematically clustered into sections dedicated to different contributions. These are: (1.) *foundations*, (2.) *materiality and gestural user interfaces*, (3.) *materiality and tangible user interfaces* and (4.) *materiality and ephemeral user interfaces*. This structure supports the relation of the chapters and sections of part one of the thesis to the corresponding publications. The publications dedicated to *conceptual foundations* provide conceptual fundamentals of and reflections on a materials perspective on HCI and are picked up in Chapters 2 and 3 of part I. The publications related to the parts *materiality and gestural user interfaces*, *materiality and tangible user interfaces* and *materiality and ephemeral user interfaces* present case studies and surveys exploring selected aspects how materiality shapes interaction. These are summarized and discussed in Chapter 4. My other publications that have not been integrated into this thesis are listed in Chapter 7.

1.5. Included Publications

The following publications are integrated into this thesis. They are fully included in Chapter 6. My personal contributions to each publication are presented in the beginning of Chapter 6.

Foundations

1.) Tanja Döring, Antonio Krüger, Albrecht Schmidt, Johannes Schöning: Tangible, Embedded, and Reality-Based Interaction. In: *it - Information Technology*, Volume 51 Issue 6, 2009. De Gruyter Oldenbourg (Berlin) 2009, pp. 319-324.

2.) Tanja Döring, Axel Sylvester, Albrecht Schmidt: Be-greifen “beyond the Surface” - Eine Materialperspektive auf Tangible User Interfaces. In: Bernard Robben, Heidi Schelhowe (Eds.): *Be-greifbare Interaktionen - Der allgegenwärtige Computer: Touchscreens, Wearables, Tangibles und Ubiquitous Computing*. Transcript (Bielefeld) 2012, pp. 115-134.

3.) Tanja Döring: The Return of the Physical: Tangible Trends in Human-Computer Interaction. In: Günther Friesinger, Jana Herwig (Eds.): *The Art of Reverse Engineering: Open - Dissect - Rebuild*. Transcript (Bielefeld) 2014, pp. 83-96.

4.) Tanja Döring: The Interaction Material Profile. Understanding and Inspiring How Physical Materials Shape Interaction. In: *Proceedings of the 2016 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM (New York) 2016, pp. 2446-2453.

Materiality and Gestural User Interfaces

5.) Alireza Sahami Shirazi, Tanja Döring, Pouyan Parvahan, Bernd Ahrens, Albrecht Schmidt: Poker Surface: Combining a Multi-Touch Table and Mobile Phones in Interactive Card Games. In: *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI'09)*. ACM 2009, Article No. 73 (2 Pages).

6.) Tanja Döring, Alireza Sahami Shirazi, Albrecht Schmidt: Exploring Gesture-Based Interaction Techniques in Multi-Display Environments with Mobile Phones and a Multi-Touch Table. In: *Proceedings of PPD 10: Workshop on Coupled Display Visual Interfaces (in Conjunction with the International Conference on Advanced Visual Interfaces AVI 2010)*, pp. 47-50.

7.) Tanja Döring, Dagmar Kern, Paul Marshall, Max Pfeiffer, Johannes Schöning, Volker Gruhn, Albrecht Schmidt: Gestural Interaction on the Steering Wheel - Reducing the Visual Demand.

In: *Proceedings of the 2011 SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM 2011, pp. 483-492.

Materiality and Tangible User Interfaces

8.) Tanja Döring, Bastian Pfleging, Christian Kray, Albrecht Schmidt: Design by Physical Composition for Complex Tangible User Interfaces. In: *Proceedings of the 2010 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '10)*. ACM (New York) 2010, pp. 3541-3546.

9.) Albrecht Schmidt, Tanja Döring, Axel Sylvester: Changing How We Make and Deliver Smart Devices: When Can I Print Out My New Phone? In: *IEEE Pervasive Computing*, 10(4), IEEE (New York) 2011, pp. 6-9.

10.) Tess Speelpenning, Alissa Antle, Tanja Döring, Elise van den Hoven: Exploring How Tangible Tools Enable Collaboration in a Multi-Touch Tabletop Game. In: *Human-Computer Interaction – INTERACT 2011: 13th IFIP TC 13 International Conference, Volume 6947 of the Series Lecture Notes in Computer Science*. Springer (Berlin Heidelberg) 2011, pp. 605-621.

Materiality and Ephemeral User Interfaces

11.) Tanja Döring, Axel Sylvester, Albrecht Schmidt: A Design Space for Ephemeral User Interfaces. In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13)*. ACM (New York) 2013, pp. 75-83.

12.) Tanja Döring, Axel Sylvester, Albrecht Schmidt: Ephemeral User Interfaces: Exploring the Aesthetics of Interface Components that Do Not Last. In: *ACM Interactions*, Volume 20 Issue 4, July + August 2013. ACM (New York) 2013, pp. 32-37.

13.) Axel Sylvester, Tanja Döring, Albrecht Schmidt: Liquids, Smoke, and Soap Bubbles: Reflections on Materials for Ephemeral User Interfaces. In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM (New York) 2010, pp. 269-270.

14.) Tanja Döring, Axel Sylvester, Albrecht Schmidt: Exploring Material-Centered Design Concepts for Tangible Interaction. In: *Proceedings of the 2012 SIGCHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '12)*. ACM (New York) 2012, pp. 1523-1528.

15.) Tanja Döring, Franziska Lorz, Rainer Malaka: Assessing the Emotional Experience of Soap Bubbles as Input Material for Interactive Games. In: Anette Weisbecker, Michael Burmester,

Albrecht Schmidt (Eds.): *Mensch und Computer 2015 - Workshopband*, De Gruyter Oldenbourg (Berlin) 2015, pp. 559-566.

2. Human-Computer Interaction Beyond the Desktop: Terminology, Interfaces, Concepts

This chapter gives an introduction to a number of current research areas in HCI focusing on interaction beyond the desktop. All of these areas cover user interfaces for *ubiquitous computing*, a term that was introduced by Mark Weiser in 1991 and denotes the seamless and pervasive integration of an increasing number of computers (in form of manifold devices and hardware elements) into our surrounding (Weiser 1991). Ubiquitous computing has become the dominating guiding theme in current computing (Rogers 2006, Abowd 2012). The HCI research community still lacks a common term for describing the novel user interfaces that are currently evolving. While the prevailing user interface within the mainframe era (ca. 1960s to 1980s) was the command line interface, and within the personal computing era (ca. 1980s to 1990s) the dominating UI was the graphical user interface (GUI), currently, in the era of ubiquitous computing, no single dominating terminology for the novel user interfaces has been established. Instead, definitions are used, that focus on what the novel UIs have overcome, e.g. “post-wimp user interfaces” (van Dam 1997) or “interaction beyond the desktop”. For specific subareas different terms have been established and some of the terms overlap to some degree. Nevertheless, all are important pillars of current interface design, and all are worth to be considered as part of a materials perspective on HCI. In the following, we describe *natural interaction*, *reality-based interaction*, *embodied interaction*, and *interactive surfaces* as embracing interaction terminology. Furthermore, *gestural interaction* and *tangible interaction* will be introduced as both interaction fields are further explored in this thesis. In the third subsection, we briefly describe important concepts for designing interaction (i.e., *mental models and mappings*, *constraints and affordances*, as well as *metaphors and image schemas*).

2.1. Embracing Interaction Terminology

This work addresses the exploration of *natural interaction*, *reality-based interaction*, *embodied interaction*, and *interactive surfaces* from a materials perspective. In the following, I will give an overview on these embracing terms.

2.1.1. Natural Interaction

The term *natural user interface* (NUI) marks a dominating trend in current HCI research, and it is as well used in popular media. In general, it addresses the idea, that designed interaction styles integrate users' skills and experiences from real life to a much higher degree than command line interfaces or graphical user interfaces do¹. Ideally, this generates user interfaces that can be easily understood and learned. The term started to become popular in 2007, when the first Microsoft Surface was announced and the first Apple iPhone came to the market. A year before, in 2006, the Natural User Interface Group (NUI group), an open source initiative media community working on natural user interfaces had been founded². In the beginning, the term NUI was mainly used for (multi-)touch gestural interaction. Further popular consumer products that have been mentioned a lot in the context of natural user interfaces are the Wii™ and the Kinect™ for Microsoft Xbox, both vision-based devices that indirectly or directly support full-body movements for system input (Francese et al. 2012). Overall, the term *natural user interface* is used in different ways and there does not exist one dominating definition yet. I will provide some views here.

First of all, the NUI term stresses a new era of user interfaces, often claimed as the new generation of user interfaces coming after the GUI (nevertheless, graphical user interfaces still play a big role in the the context of NUIs, as graphical output is often part of it). The important idea is that a system matches a user's expectations and fits his or her learned skills:

“A reasonable operational definition for a natural UI is that the experience of using a system matches expectations such that it is always clear to the user how to proceed and only a few steps (with a minimum of physical and cognitive effort) are required to complete common tasks.” (Hinckley and Wigdor 2012, p.100)

These acquired skills could be motor sensual, cultural, cognitive, social and emotional.³

In their book “Brave NUI World” Wigdor and Wixon (2011) argue that not the interface itself is meant to be natural. Rather, they “see natural as referring to the way users interact with and feel about the product, or more precisely, what they do and how they feel while they are using it” (Wigdor and Wixon 2011, p. 9). Thus, the “natural” in *natural user interface* does not refer to the interface, but rather addresses the way users should behave and feel when using the UI (cf., Wigdor and Wixon 2011, p. 11). Thus, NUIs should not mimic the real world but rather create experiences that, for expert users, can feel like an extension of their body (Wigdor and Wixon 2011, p. 13). In order to illustrate this, Wigdor and Wixon give the example of the first apple pad, the Newton Message Pad, which did not succeed. Among the problems it had was the handwriting recognition, that was aimed to recognizing real handwriting, which did not work. An

¹Cf., “A natural user interface is a user interface designed to reuse existing skills for interacting appropriately with content.” (Blake 2010, p. 4).

²<http://nuigroup.com/log/about/> (last access: October 5th, 2016).

³For a discussion on natural user interfaces see the panel at TEI 2012. A video recording is available on <http://www.ustream.tv/recorded/20624353> (last access: October 5th, 2016). Within this, Bill Buxton stresses the importance of specific user groups and the tasks and context an interface is used in. Thus, a user interface can be only regarded as natural, if it fits the users, tasks and contexts.

opposite example is the Palm Pilot that came out 1997 and used a special handwriting language called “Graffiti”. Graffiti is similar to single character handwriting but simplifies the symbols – this made the recognition easier but at the same time required some learning by the users. Nevertheless, for Wigdor and Wixon this is an example for a successful natural input technique that does work, because it does not mimic reality, but still feels natural to the users. In their book, Wigdor and Wixon describe a number of further aspects they regard as crucial for natural user interfaces, among which are that NUIs should be enjoyable, leading to skilled practice and be appropriate to context (Wigdor and Wixon 2011, p. 29).⁴

In most cases the term *natural user interface* is used for gestural interaction, both touch or mid-air interaction, pen interaction and sometimes also for speech input. Generally, it could encompass all possible interaction modalities, for input as well as for output (but so far, the focus was more on input) (Jain et al. 2011). As such, natural user interfaces are related to the research field of multimodal interfaces. Oviatt describes multimodal systems as follows:

“Multimodal systems process two or more combined user input modes – such as speech, pen, touch, manual gestures, gaze, and head and body movements – in a coordinated manner with multimedia system output. [...] This new class of interfaces aims to recognize naturally occurring forms of human language and behavior, which incorporate at least one recognition-based technology (e.g. speech, pen, vision).” (Oviatt 2012, p. 405)

NUIs are often described to be “intuitive”. This term also is strongly related to users’ previous knowledge and the idea, that the focus of the user is on the content and not on the user interface.⁵ In order to let an interaction be regarded as natural and to keep the learning overhead small, the design of appropriate mappings (see Subsection 2.3.1 below) of commands to interactions, e.g. through gestures, is important. This is a central challenge in current user interface design and research. As Norman (2010) argues, design principles as *easy memorability*, *user feedback* or consistent *conceptual models* are as important for natural user interfaces as for GUIs. The design of NUIs is challenging as “natural mappings” for commands in most cases do not already exist, they have to be learned by the user and established by the UI designers and technology producers. What feels natural, depends not only on the task, but also on the specific culture a user comes from, etc. Thus Norman argues, that “natural user interfaces are not natural” and the term in this sense is misleading (Norman 2010).

Nevertheless, novel technologies always need time to establish, and it is one of the current major challenges in user interface design to design interaction styles that feel as natural as possible –

⁴More recently, Preim and Dachselt published the following definition for natural user interface (in German): *“Eine natürliche Benutzungsschnittstelle ist ein System zur Mensch-Computer-Interaktion, mit dem Benutzer mittels intuitiver und zumeist direkter Bedienhandlungen interagieren, die einen klaren Bezug zu natürlichem, realweltlichem menschlichen Alltagsverhalten aufweisen. Natürlich heißt dabei nicht angeboren, sondern bezieht sich auf dem Benutzer durch den Alltag vertraute und erlernte Handlungen bzw. auf solche Handlungen, die Benutzern im Moment der Interaktion als angemessen erscheinen.”* (Preim and Dachselt 2015, p. 472).

⁵See, for example, the definition by Naumann et al.: “A technical system is, in the context of a certain task, intuitively usable while the particular user is able to interact effectively, not-consciously using previous knowledge.” (Naumann et al. 2007, p. 129).

keeping in mind, that interaction techniques always have to be learned to some degree. The NUI approach dominates HCI research and can be found also in specific research fields such as 3D user interfaces (Bowman et al. 2012) or automotive user interfaces (Pfleger et al. 2011b).

2.1.2. Reality-based Interaction

(Jacob et al. 2008) addressed the lack of terms for the evolving class of “post-wimp” user interfaces by introducing the *reality-based interaction* framework as a framework that allows to discuss aspects of the multitude of current user interfaces “beyond the desktop” in a structured way by identifying and analyzing aspects of reality and computational power that are useful for interaction. The authors assumption is that “basing interaction on pre-existing real world knowledge and skills may reduce the mental effort required to operate a system because users already possess the skills needed” (Jacob et al. 2008, p. 204). Jacob and colleagues argue that interaction designers should always start from the knowledge and skills humans have gathered in the real world. This potentially helps to reduce the *gulf of execution* (Hutchins et al. 1985). The authors suggest four themes of experiences and skills derived from reality: (1.) *naive physics*, (2.) *body awareness and skills*, (3.) *environment awareness and skills*, and (4.) *social awareness and skills*.

Naive physics includes all the knowledge and experiences humans have collected about physical laws, like gravity, friction, mass, stiffness, weight etc. The theme *body awareness and skills* comprises the knowledge about the own body: how it can be moved to achieve a specific movement or how a certain movement feels. *Environment awareness and skills* contains human knowledge and skills regarding orienting and navigating in the environment, e.g., humans are able to use landmarks to orient themselves. The fourth topic, *social awareness and skills*, addresses the knowledge and skills humans have in relation to other humans, e.g., different ways of talking to others depending on the situation, different distances that are appropriate or not in specific situations, etc. These reality-based themes can play a role within interaction design. To give some examples, e.g., friction as a principle based on gravity has been metaphorically applied to graphically presented data on touch user interfaces. I.e., when the user slides in the address book on an android phone for example, the sliding movement slows down, to make the movement experience more realistic (*naive physics*). Knowledge and skills about how to move the own body, how to use kinesthetic and proprioceptive feedback, is important for full-body or hand movement interaction, e.g., realized in Kinect Games (*body awareness and skills*). The human capabilities to orientate and navigate in the environment are very important design factors for map and navigation applications (*environmental awareness and skills*). And, last, *social awareness and skills* play a role in social networks or in the virtual world of *Second Life* for example, where the users’ communication still is based on their learned social skills.

Although most of the novel user interfaces are based on humans’ experiences from the real world to a stronger degree than it used to be, computer tools and applications would not be as powerful, if systems were based purely on reality-based themes. Computers have many advantages, called “computational power” by Jacob et al., among which are *Expressive Power*, *Efficiency*, *Versatility*,

Ergonomics, Accessibility and Practicality. E.g., when searching for a document where the title is known, it is much more efficient to search in digital documents by typing in search terms than browsing through a pile of physical documents (which would be the more reality-based way to do it). Thus, one of the central challenges of current user interface design lies in the combinations of and tradeoffs between computational power and reality. Jacob et al. “propose that the goal is to give up reality only explicitly and only in return for other desired qualities” (Jacob et al. 2008, p. 205).

2.1.3. Embodied Interaction

While human-computer interaction used to mainly focus on hardware and software as artifacts that are separated from the environment of their users, the concept of *embodied interaction* strongly relies on an integration of interaction between humans and computers into the material and social environment. This new quality of situatedness of interaction techniques with computers into our daily environment makes a “new perspective on the relationship between people and systems necessary” (Dourish 2004, p. 192). Dourish (2004) called this new perspective *embodied interaction* and described it as follows:

“Embodied Interaction is the creation, manipulation, and sharing of meaning through engaged interaction with artifacts.” (Dourish 2004, p. 126)

Drawing from theories of embodiment in psychology, sociology and philosophy, Klemmer et al. (2006) discuss five themes of embodiment that matter within interaction design: *thinking through doing, performance, visibility, risk, and thick practice.* With *thinking through doing* the authors address research from embodied cognition, that “regard bodily activity as being essential to understanding human cognition” (Klemmer et al. 2006, p. 141). Learning through doing is an area, e.g. addressed by Jean Piaget, who looked at the importance of physical activity in early childhood to facilitate cognitive development or applied in the Montessori method. Furthermore, the importance of gestures and epistemic actions (“manipulating artifacts to better understand the task’s context” Klemmer et al. 2006, p. 141) to facilitate mental work have been proven in research. In interaction design, product design and architecture, the value of physical prototypes and models early on and iteratively in the design process is without controversy. These “conversations with materials”, as Schön (1984) called them, are needed because designers need the physical representations to better understand the design challenges. With *performance* Klemmer et al. (2006) address the rich sensorimotor skills and tacit knowledge humans can develop, especially within expert domains. The high tactile acuity and the bimanual asymmetric capabilities of humans’ hands are yet barely used for human-computer interaction. This is similar with kinesthetic memory, so that there is a huge potential in using the body skills further for HCI, especially as many bodily responses can be acted out without explicit cognition and thus are very fast. The next two themes focus on social context, incorporating more than one user. The theme *visibility* subsumes visible aspects of work practices that allow for peripheral participation and facilitate coordination. While the graphical user interface does not make many work practices transparent, working with artifacts in space leaves more opportunities for understanding, participation, com-

munication and coordination: “The visibility of a work practice manifests itself in the artifacts that the practice creates” (Klemmer et al. 2006, p. 144). In their fourth theme, *risk*, Klemmer et al. (2006) argue that physical action always take place with a “risk” (e.g. no easy “undo” is possible as in typical GUI applications) and that this can be beneficial in certain situations, as it can evoke more trust, a stronger commitment, responsibility or better attention. The last theme, *thick practice*, addresses that fact that our interactions with real objects are so manifold and rich that a replacement of work practices through traditional computer systems with graphical user interface necessarily always lose some of these practices. Thus, the authors argue that “because there is so much benefit in the physical world, we should take great care before unreflectively replacing it” (Klemmer et al. 2006, p. 147).

2.1.4. Interactive Surfaces

Next to other terms, the term *interactive surfaces* is used as an umbrella term for a variety of interactive displays beyond the desktop including interactive tabletops, interactive walls, interactive floors, multi-display environments like the combination of large screens and small devices, or interactive arbitrarily shaped objects and displays. Early ideas focusing on interactive screens beyond the desktop were developed in the early 1990ies at Xerox Parc, where Weiser et al. suggested “tabs, pads and boards” as differently sized devices for ubiquitous computing: “inch-scale machines that approximate active Post-it notes, foot-scale ones that have something like a sheet of a paper [...] and yard-scale displays that are the equivalent of a blackboard or bulletin board.” (Weiser 1991, p. 98). When reviewing the development of ubicomp products 20 years after Weiser published his vision, Ebling and Baker found that we clearly have all these kinds of devices today, but we have not reached the desired interoperability yet (Ebling and Baker 2012). Nevertheless, there has been a strong focus on interactive surfaces within HCI research in the last 20 years. Further pioneering work came from the Parc EuroLabs. In their 1993 special issue in the journal “communication of the ACM” Wellner, Mackay and Gold stated that “*from the isolation of our workstations we try to interact with our surrounding environment, but the two worlds have little in common.*” (Wellner et al. 1993) and in order to overcome this problem they suggested *computer-augmented environments*: systems, where electronic systems are merged into the physical world. An influential prototype coming from this lab is the “digital desk” – one of the early examples of interactive tabletops (if not the earliest). The “digital desk” by Pierre Wellner (Wellner 1993) augmented a real desk and ordinary paper on it with a digital system, e.g. a calculator that calculated sums from numbers printed on paper by pointing to them. The calculator prototype was realized by using cameras, microphones and image processing software in order to capture the needed data. For visual output, a projector was installed above the tabletop, facing towards the desk. This early example was a predecessor of many further interactive tabletops, for example the “InteracTable” published as part of an interactive office landscape called “i-LAND” (Streitz et al. 1999). In this conceptual prototype office environment, Streitz and colleagues designed a number of interactive roomware components: next to the “InteracTable” also an interactive wall (“DynaWall”), interactive chairs (“CommChairs”) as well as a mechanism to link data to physical objects and transfer the data to different devices by simply putting the object onto a device (the “passage concept”). Especially the opportunity to create workspaces for groups of people was

and is a motivation for research on interactive tabletops and walls. Further pioneering research in this area came from the former tabletop research group at Mitsubishi Electric Research Laboratories (MERL) that invented and developed the “DiamondTouch” Table, an interactive tabletop system, which was based on capacitive coupling using a grid of antennas that are connected to separate receivers via users that touch the antenna grid of the interactive surface (Dietz and Leigh 2001). Among the advantages this system offers is that it allows to distinguish different users when they touch the interactive surface. The MERL research group also addressed other central tabletop research questions and usability challenges like occlusion and reach, content orientation or gestural interaction (Shen et al. 2006). Further relevant topics have been identified by Scott and colleagues (Scott et al. 2003), who collected and identified system guidelines for co-located collaborative work on tabletop displays, e.g. addressing the support of transitions between personal and group work, the use of physical objects, the provision of shared access, or the support of simultaneous user actions.

With Jeff Han’s demonstrations and publications on how to utilize the principle of frustrated total internal reflection (FTIR) to realize a multitouch surface (Han 2005), tabletop research became widespread within HCI institutions and university groups as this technology allowed to build tabletop systems comparably cheap and easy. In the general setup, infrared (IR) light is beamed into a sheet of acrylic glass from the borders. Due to the higher material’s density compared to the surrounding air, the infrared lights normally stays inside the acrylic glass (total internal reflection). Only if the surface is touched, the IR light gets distracted at this spot, such that a camera below the tabletop can detect it and an image processing software can calculate the coordinate. As this principle works for many contact points at once and scales up to relatively large surfaces it presents a very powerful approach for the research community. Graphical output can be integrated easily as well using standard – or short-throw if installed below the table – projectors in combination with projection screens on or below the surface. An influential commercial product that as well applied visual tracking was the early Microsoft Surface table that was released in 2008 and followed in 2012 by the Microsoft PixelSense, using the PixelSense technology, which had optical sensors integrated in its surface. Next to tabletop systems also research on interactive wall displays (e.g., Rogers and Lindley 2004), among these for example on public displays (e.g., Müller et al. 2010), became major research strands. But interactive surfaces furthermore include a variety of other types like combined horizontal and vertical displays (e.g., Weiss et al. 2010), interactive floors (e.g., Augsten et al. 2010), and rollable (e.g., Khalilbeigi et al. 2011) or foldable displays (e.g., Khalilbeigi et al. 2012). Interactive surfaces of non-flat shapes are addressed in further depth by Vertegaal and colleagues, who promote the term *organic user interfaces* (OUIs), defined as follows:

“An Organic User Interface is a computer interface that uses a non-planar display as a primary means of output, as well as input. When flexible, OUIs have the ability to become the data on display through deformation, either via manipulation or actuation. Their fluid physics-based graphics are shaped through multi-touch and bi-manual gestures.” (Holman and Vertegaal 2008, p. 52)

In further detail, OUIs focus on (1) “input equals output”, i.e. a unified input and output space where manipulations of the output device are interpreted as input, (2) “function equals form”,

i.e. a focus on shape as input and output modality that triggers the functionality according to the context, and (3) “form follows flow” (Holman and Vertegaal 2008).

With the wealth of types of interactive surfaces, the combination of different interactive surfaces yields increasing potential. Especially the combination of private and public screen, e.g., by using mobile phones and large surfaces together. Jun Rekimoto was among the pioneers who identified potentials and challenges of multi-display environments and suggested for example “Hyperdragging” as interaction technique for “augmented surfaces”: a pointing technique that allows to drag a cursor beyond screen barriers onto other devices, no matter if laptop, tabletop or wall screen (Rekimoto and Saitoh 1999). Coupling displays still is an important research area addressed for many different setups, e.g. between mobile devices, between mobile devices and interactive tabletops, or between mobile devices and interactive walls. For coupled display ecosystems, Terrenghi and colleagues have developed a taxonomy focusing on *the scale of multi-person display ecosystems* and *the nature of social interaction* (Terrenghi et al. 2009). In this taxonomy, *the scale of the ecosystem* is divided into 5 types: *inch size ecosystem*, *foot size ecosystem*, *yard size ecosystem*, *perch size ecosystem*, and *chain size ecosystem*, depending on the interaction space in which the users have to move their eyes. The *social interaction* is divided into *one-one*, *one-few*, *few-few*, *one/few-many*, and *many-many* relating to the involvement of users who interact with the connected screens. Both axis of attributes, scale and social interaction, can be combined to discuss different classes of multi-person display ecosystems.

2.2. Gestural and Tangible User Interfaces

Next to *ephemeral user interfaces* that will be introduced and defined as part of this thesis’ research in chapter 4 and related publications, the focus of this work is on *gestural and tangible user interfaces*.

2.2.1. Gestural User Interfaces

Gestural Interaction is among the most popular trends within HCI and UI design for products nowadays. The term *gestural interaction* comprises different kinds of interaction forms that all realize gestures, but in varying ways and settings. E.g., gestural interaction can be performed on interactive surfaces as done in single or multi-touch interaction. These gestural interactions on surfaces can either be performed with fingers, but could also involve further objects as pens for example. Another approach to use gestures for interaction is to design mid-air gestures, this again could include arm and hand movement but also the integration of further active or passive objects like mobile phones or props. For this type of gestural interaction with physical artifacts, Van den Hoven and Mazalek introduced the term *tangible gesture interaction* (Van Den Hoven

and Mazalek 2011)⁶ Furthermore, gestural interaction could even include larger parts of the body beyond arm and hand gestures.

Within human-computer interaction gestural interaction has been of interest since the early days of the discipline. One of the pioneers who realized systems where gestures were tracked and used to interact with a computer is Myron Krueger (Krueger 1983). From end of the 1960ies on he built a number of very innovative *responsive environments* where he used a large repertoire of gestures for interaction. For example, in his 1985 environment “Videoplace” Krueger et al. (1985) realized the pinch gesture, which is widespread today to resize and rotate pictures (see also Buxton 2012). Another well-known example for early gestural interaction is Bolt’s “Put-that-there” interaction technique, developed in MITs Architecture Machine Group, where pointing gestures were combined with speech interaction in order to interact with a wall display (Bolt 1980). Also multi-touch gestural interaction, although widespread only since Jeff Han’s 2005 presentation (Han 2005) as well as Apples first iPhone and the first Microsoft Surface table in 2007, had been applied in a large number of research prototypes for many years; for an overview see (Buxton 2012).

For the application of gestures in human-computer interaction, Kurtenbach and Hulteen (1990) formulated the following definition:

“A gesture is a motion of the body that contains information. Waving goodbye is a gesture. Pressing a key on a keyboard is not a gesture because the motion of a finger on its way to hitting a key is neither observed nor significant. All that matters is which key was pressed.” (Kurtenbach and Hulteen 1990, p. 310)⁷

Gestures as used in the communication between humans have been studied for a while and should be considered when designing gestural interaction for the communication between humans and computers. Kendon (1988), for example, introduced a taxonomy of gestures, in which different gesture types are ordered on a continuum according to their level of speech dependency. Among gestures that are only accompanying speech are *gesticulation* (e.g. beat gestures and cohesives, see also McNeill 1992) and *language-like (iconic) gestures*. While *beat gestures* could e.g. express the rhythm of speech, *iconic gestures* contain more information, e.g. relating the size or movement of objects. *Pantomimic gestures* form the next class of gestures and depict gestures that visualize processes by assuming imaginary objects. Further independent of speech are *emblems*, gestures that are based on symbols (they also contain *deictic gestures*). Last, the gesture class *sign language* even works independent of speech and gives a complete set of vocabularies that can be used instead of speech. For the context of HCI, Preim and Dachselt suggest to distin-

⁶They presented the following definition: “We define tangible gesture interaction as the use of physical devices for facilitating, supporting, enhancing, or tracking gestures people make for digital interaction purposes.” (Van Den Hoven and Mazalek 2011, p. 265).

⁷More recently, Preim and Dachselt gave the following definition for gesture (in German): “Eine Geste ist die Bewegung von Fingern, Händen und Armen – oder auch weiterer Körperteile, wie Kopf, Augen und Lippen – aufgrund einer kommunikativen Absicht. Damit enthält die Bewegung als solche signifikante Informationen, die an den Computer übermittelt werden sollen.” (Preim and Dachselt 2015, p. 497).

guish the following types of gestures: *deictic gestures*, *manipulative gestures*, *symbolic gestures*, *sign language* and *speech-accompanying gestures* (Preim and Dachsel 2015, p. 499).

Within human-computer interaction so far mainly emblems have been applied in gestural interaction (cf., Billinghurst and Buxton 2009, Hummels 2000), while there should be many potentials to apply gestures in combination with speech, as can be seen from our everyday use of gestures (for an example, see Pfleging et al. 2011a). Another problem of using emblems is that many of them have to be learned by their users. In order to reduce this learning effort and to find gestures that are as intuitive as possible, many interaction designers recently applied the method of user-elicited gestures. With this method, potential users are asked to find and perform gestures for certain commands. This method has been applied by Wobbrock et al. (2009) for example, who asked participants in a study to perform basic commands for a multi-touch tabletop setup. Analyzing the results, they found different strategies users applied to design the gestures, e.g. based on symbolic, physical, metaphorical or abstract models. In addition to the challenge how to optimally design gestures that can easily be understood and learned it is still challenging to build a reliable gesture recognition, depending on how complex the gestures are (cf., Lee 2010).

Among the advantages of gestural interaction is that bimanual interaction can be realized within human-computer interaction; especially in the context of multi-touch interaction this has been discussed (Wagner et al. 2012, e.g.). Guiard (1987) studied bimanual interaction and found “an asymmetric division of labor”: in many tasks, one hand sets the spatial referential frame for the other, e.g. we first fix the orientation of a piece of paper on a tabletop surface with the non-dominant hand and then write with the dominant hand. Guiard modeled hands as abstract motors that “correspond(s) to a temporal-spatial scale” (Guiard 1987). Guiard’s insights do not only mean that the two hands perform different tasks that relate to each other but also that the kind and frequencies of movements typically differ (see also discussion in Hummels 2000). This should be considered when designing for bimanual interaction. Domains where Guiard’s model has been applied to multitouch applications are, for example, 3D-modeling (Herrlich 2013) and computer animation (Walther-Franks 2014).

2.2.2. Tangible User Interfaces

The central idea of tangible user interfaces (TUIs) is to connect real objects with digital data and thus to enable the interaction with the data via interaction with the objects. The word “tangible” comes from the latin word “tangere”, which means “to touch, to grasp”. Users can literally grasp data and manipulate it by manipulating objects with their hands. Tangible user interfaces became popular in the research community with the work conducted by Ishii and Ullmer et al. at MIT Media Lab in the 1990s and 2000s. In their “Tangible Bits” paper in 1997, they describe the overall concept and part of ubiquitous computing where the whole world around us potentially becomes an interface (Ishii and Ullmer 1997). Ishii and Ullmer describe TUIs as follows:

“The key idea of tangible interfaces is giving physical form to digital information. These physical forms serve both as representations and controls for their interwoven

digital bindings and associations. TUIs make digital information directly manipulable with our hands, and perceptible through our foreground and peripheral senses.”
(Ishii and Ullmer 2012, p. 466)

The central idea of tangibles is that the materials used for physical devices and the shapes they come in directly embody digital information. Hemmert (Hemmert 2014, p. 36) defines this aspect as *representational embodiment* as opposed to *experiential embodiment*, which refers one’s experience of the world through having a living body (Hemmert 2014, p. 44). To shape this representational embodiment of a device, interaction designers and end user designers have to face material decisions as a very central design issue of the interaction. While this is generally true for interaction and product design, its significance in tangible interaction design in particular is much bigger as the interactions are directly shaped by the material.

Two early prototypes with tangible user interface that nicely present the basic ideas connected to tangibles are the “Marble Answering Machine” by Durell Bishop and the “Dangling String” by Natalie Jeremijenko. Both are mentioned in (Ishii and Ullmer 1997) and (Dourish 2004). The “Marble Answering Machine”, which was conceptually designed as part of a master thesis project at the Royal College of Art in London, is an answering machine, where incoming messages are presented in form of real marbles. If a message has been left on the machine, a marble rolls down a track, where it stays together with other marbles, each of them presenting present messages. At a glance, a user can see the number of messages and by manipulating them, can either play a message (by putting the associated marble into a specific track in the machine), erase it (by putting it into a hole), save it for other family member (by putting it into a dedicated bowl), annotate it (putting them onto a “todo” shelf, adding further notes simply by writing with a pen onto the shelf), or calling back the person that left the message (by directly putting the marble into the telephone). This concept of a tangible user interface shows how digital data, in this case the voice message, can be represented by graspable objects and how functions with this data can be triggered by manipulation of the real objects. This potentially leads to more meaningful ways to interact than just by pressing on arrays of buttons that are arbitrarily mapped to certain functions. Another design work, the “dangling string” (also called “live wire”), was installed in Xerox Parc in 1994 and already described by Weiser and Brown (1996) as an example how ubiquitous computing could look like. The dangling string was a plastic string that hung vertically from the ceiling. At the top, it was connected to a step motor that was activated according to traffic in the local ethernet, such that the string moved heavier the more traffic occurred. This art piece is an example for ambient media that is intended to function at the periphery of human perception, while the Marble Answering Machine is intended to be at the center of a user’s perception (cf., Ishii and Ullmer 1997). Both examples are tangibles that show how digital information can be integrated into the physical world in a more seamless way.

While TUIs started to be on the research agenda on many HCI groups by the end of the 1990ies, there had been precursors of tangible user interfaces. One example is a 3D modeling system by John Frazer and colleagues, that created a virtual 3D model by sensing the arrangement of tangible building blocks (Frazer et al. 1980). Frazer is an architect and was motivated to work on physical user interfaces, because he did not regard mouse and keyboard as appropriate for computer-aided architectural design. Furthermore, he wanted to support participatory and itera-

tive design in architecture and in order to facilitate this, he worked on pluggable physical models, a kind of electronic bricks, that could be used as input mechanism to generate digital models, on which further calculations (e.g., energy consumption) could be conducted. Frazer called these systems “intelligent physical modelling systems” (Frazer et al. 1980, Frazer 2010).⁸

Within computer science an early research project on tangible user interfaces was a system offering physical handles (called “Bricks”) to control graphical representations, shown on a horizontal surface (Fitzmaurice et al. 1995). Fitzmaurice, Ishii and Buxton called the concept “graspable user interface”. In their concepts and in a working drawing prototype, the manipulation of single or pairs of physical bricks were mapped to functions in the application, e.g. select, rotate, or scale an object. In their research, the authors specifically highlight the advantages of space multiplexing in user interfaces, bimanual input as well as specialized physical form factors for input devices (Fitzmaurice and Buxton 1997). Hiroshi Ishii proceeded working on tangible user interfaces when he came to MIT Media Lab. Among the early prototypes developed in the Tangible Media Group were “Urp” and “Illuminating Clay”, two user interfaces for urban planning and landscape design. Urp (Underkoffler and Ishii 1999) is an interactive surface on which abstracted models of buildings could be placed in order to work collaboratively on urban planning. The system provided a number of simulation function, e.g. airflow, light and shadows, that could be triggered and parameterized by a physical control panel (containing a clock) and a magic wand and displayed on the table via graphical output. Similarly, Illuminating Clay (Piper et al. 2002) allowed simulations, e.g. water drain, and provided information, e.g. contour lines, presented as graphical output on a landscape model. The landscape model itself was made of clay and could be directly molded by hand. Both of these systems provide tangibles for input and unify input and output space by providing graphical feedback within the same area where the tangible input takes place.

An early system with tangible user interface that has evolved into a product, is the “reactable” (Jordà et al. 2007), a tabletop-based electronic music instrument using abstract tangibles as controllers, allowing to use the whole tabletop space as input area and many controllers in parallel, such that the instrument can be collaboratively played. Manipulations of the tokens, together with touch input, are mapped to functions that change certain parameters. The reactable was developed at the University of Pompeu Fabra in Barcelona and uses camera-based tracking together with specially developed fiducials that, if attached to an object, allow the detection of the object ID, location and orientation on the tabletop surface. The associated computer vision framework reactIVision⁹ has been made available as open source tool and became an important and widely used toolkit for tangible multi-touch surfaces.

Having looked at these examples for tangibles, the remainder of this section will summarize some general principles of TUIs. One way to structure the elements of tangible user interfaces is to apply the Model-View-Controller pattern that was formulated in Xerox Parc as part of the Smalltalk-80 system (Reenskaug 1979) and that is used as design pattern in software engineering. In this pattern, the *model* consists of digital data files with application data, *control* elements

⁸An overview on Frazer’s work can be found in his book “an evolutionary architecture” (Frazer 1995).

⁹<http://reactivision.sourceforge.net/> (last access: October 8th, 2016).

are typically the mouse and keyboard and the *view* is the visual representation. Ullmer and Ishii (2000) developed a corresponding interaction model for TUIs, the MRC_{it} interaction model, and revised it in (Ishii and Ullmer 2012). In this model, the view part is split into representation physical and representation digital. Furthermore, while in the GUI system view and control parts are to a large degree still based in the digital, in the TUI model, control and representation takes place to a higher degree in the physical world. This model visualizes three key properties of tangible user interfaces (Ishii and Ullmer 2012): (1) *computational coupling of tangibles to digital information*, (2) *tangible embodiment of mechanisms for interactive control*, and (3) *perceptual coupling of tangibles to intangible mediations*. First, in TUIs, physical objects are computationally coupled to the model, e.g. in case of the Marble Answering Machine, real marbles represent digital voice messages. Second, tangibles are used for control, i.e. the manipulation of physical objects is mapped to functions on the digital data. In case of the Marble Answering Machine, e.g. the “play”, “delete” or “store” a message functions are triggered by putting the corresponding marble into dedicated locations. And third, tangible and intangible representations are perceptually coupled. Again looking at the Marble Answering Machine, this means a marble and a sound file together represent a message. Most tangibles (additionally) use graphical output (e.g. projections) as intangible representation. For the UI designer, this combination of physical and digital representation generally bears the challenge to decide which parts of a TUI should be digital and which physical.

Furthermore, TUIs offer a number of characteristics that affect interaction with computers. Among these are that tangibles can give immediate tactile feedback, naturally provided by real objects that are used for interaction, that they offer a double interaction loop, that they persist, even if they are “offline”, and that they realize space-multiplexed input (Ishii and Ullmer 2012). In general, TUIs are rather used as special purpose user interfaces than as generic UIs, as it is difficult to design meaningful interaction objects that fit any context. The coincidence of input and output spaces is a further characteristic that ideally is applied in TUIs (Fishkin 2004, Ishii and Ullmer 2012), thus realizing direct interaction instead of indirect interaction where input and output space are separated (as with the mouse and the graphical user interface for example).

2.3. Concepts for Designing Interaction

In this section important concepts for designing gestural, tangible and ephemeral user interfaces are presented. The subsections introduce *mental models and mappings*, *constraints and affordances*, as well as *metaphors and image schemas*.

2.3.1. Mental Models and Mappings

Based on previous experience, humans build *mental models* in order to plan actions or solve problems. These “mental models are schema that contain relations, terms, assumptions and men-

tal maps, which allow us to think about devices and systems in a structured way.” (Preim and Dachsel 2015, p. 94, translated into English). I.e., they help users to understand how an interaction with computers works based on their own experience. This experience usually either stems from their knowledge about the material world (Jacob et al. 2008), e.g., from *real affordances* (see next subsection), *applied affordances*, from *cultural conventions*, *physical constraints*, and *logical constraints* (Norman 1999), amongst others, or from their knowledge about using other devices (Jetter et al. 2014), in which previously mental models partially based on the material world have been developed and mixed with computational power and magic. When we design interactions, it is important to build upon existing mental models as well as to support forming appropriate new ones. Norman calls these mental models that developers and interaction designers apply *conceptual models* for the interaction (Norman 1983).

A *mapping* is a perceivable relation between user interface elements and their effects. Norman (1988) argues to design everyday things with mappings that appear natural, i.e., that use spacial analogies and cultural conventions. A good mapping is therefore, that turning a steering wheel to the left affects a left turn of the vehicle (according to spacial analogies, but nowadays as well culturally established). When designing tangibles, UI designers specifically have to address the question of mappings, as everyday objects around us suddenly become interfaces, and it should be easy to understand for users what functions or data these are mapped to and how a manipulation of the objects is mapped to the data. For good mappings, *constraints* and *affordances* can be used.

2.3.2. Constraints and Affordances

In his book “The design of everyday things” Norman (1988) introduced four classes of *constraints* that are important for user interface design: *physical constraints*, *semantic constraints*, *logical constraints* and *cultural constraints (conventions)*. All four constraints can guide user interaction, as they offer cues about what is possible with an interface. *Physical constraints* use physical properties, like shape, to allow or prohibit certain manipulations. They play an important role in tangible user interface design, as concept of TUIs strongly rely on the manipulation of objects, especially on the shapes, the materials, or the surface properties of objects. As data is controlled via manipulating objects, physical constraints directly guide which digital functions are possible. Ullmer and Jacob used this to develop their “token and constraint” approach (Ullmer et al. 2005) where differently shaped objects can be placed into trays, allowing a different number of degrees of freedom for movements. While physical constraints can even make certain actions impossible, *semantic*, *logical* and *cultural constraints* are somewhat weaker, as they guide interaction based on knowledge and experiences, but do not prohibit semantically, logically or culturally unusual interactions. Nevertheless, all three still are strong concepts, especially as the related knowledge generally is long-term established and thus should be considered by the designer. *Semantic constraints* relate to meaningful configurations, e.g. when assembling a LEGO toy motorcycle, the rider should sit facing forward. An example for a *logical constraint* would be, that an array of switches is mapped to an array of lights in the same spatial order, i.e. the leftmost switch controls the leftmost light. *Cultural constraints* can be manifold and are shared by a community. Estab-

lished conventions, such as how to move files on a virtual desktop or how mouse pointers are represented on a screen, are examples for cultural constraints.

The term *affordances* was coined by the perceptual psychologist James Jerome Gibson in 1977 (Gibson 1977). Starting from the verb “to afford”, he established *affordances* as a term for what the environment or objects offer actors, who can be humans or animals. For example, a horizontal, flat, extended and rigid surface affords support and thus is stand-on-able, walk-on-able, or run-over-able amongst others (Gibson 1979, p.127), while a vertical surface does not afford walking, but – depending on the actor – maybe climbing. An important aspect of Gibson’s theory is, that affordances are not abstract physical properties, but must be seen as relative to the actor’s abilities and properties. For example, a normal chair affords sitting for an adult, but not for a baby. Gibson sees an affordance as an “invariant combination of variables” (Gibson 1979, p.127) that does not change when the need of the observer changes (as opposed to the concept of valence). The term *affordance* was brought to human-computer interaction in 1988 by Donald Norman in his book “The design of everyday things” (Norman 1988) and, later, by Gaver (1991). Since then, the theory of affordance has been applied differently. The term and its meaning in the context of HCI is still discussed controversially, cf., (Hornecker 2012) and (Kaptelinin and Nardi 2012). Norman first introduced it as following: “the term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used” (Norman 1988, p. 9). In contrast to Norman, Gibson had defined affordances as existing without the need to be perceived by actors. After Norman had brought the term to HCI, it was picked up intensely and often used for visual properties of GUI elements, which was not in line with the original definition, that referred to physical properties. As a response to this, Norman published an article in 1999, stating that his affordance term was meant to describe *perceived affordances* rather than real, physical affordances (Norman 1999). In the meantime, William Gaver had proposed to use the concept of affordances as a tool to analyze technologies in user-centered design (Gaver 1991). He gave the following definition:

“The concept of affordances points to a rather special configuration of properties. It implies that the physical attributes of the thing to be acted upon are compatible with those of the actor, that information about those attributes is available in a form compatible with a perceptual system, and (implicitly) that these attributes and the action they make possible are relevant to a culture and a perceiver. Artifacts may be analyzed to see how close they are to this configuration of properties, and thus what affordances they convey.” (Gaver 1991, p. 81)

Gaver distinguishes between *perceptible affordances*, i.e. affordances that offer perceptual information, *hidden affordances*, i.e., when there is no information available, and *false affordances*, i.e. if there is information available that suggest acting upon a non-existent affordance. Furthermore he argues, that affordances can be also perceived by other modalities (senses) than visually, e.g., haptically or auditive. Overall, Gaver sees the concept as a powerful approach that focuses neither only on the users or the technology, but on the interaction between both.

Within tangible Interaction, affordances play a big role, as physical properties of real objects are directly used for interaction (while, in GUI design, these only serve as a model that is applied metaphorically, which can result in – what Norman calls – *perceived affordances*). E.g., Baskinger and Gross (2010) highlight the importance of shape for TUIs and the potential to use physical form to mediate and facilitate interaction. Nevertheless, objects have manifold affordances, and 20 years of tangible user interface design have shown that it is difficult for UI designers to make clear to the user, which affordances of an object are utilized for the interaction. E.g., systematic studies looking at the manipulation of cubes of different sizes, shapes and materials revealed a huge variety of different actions (Sheridan and Kortuem 2006). This makes it almost impossible for the designer to anticipate the users' reaction to an interface (Hornecker 2012). To make it worse, tangibles have a hybrid nature, they combine physical and digital system parts, and do not mimic real world behavior, but add “magic”. This means, we can not just apply real world knowledge, like our experiences with the affordances of objects, to the interaction with tangibles without learning in what way they are used and how they are combined with magical rules. As this often has led to confusion and as her literature review revealed an “under-utilized conceptual depth” of the concept of affordances, Hornecker (2012) suggests to rethink potentials and limitations of affordances for tangible interaction.

2.3.3. Metaphors and Image Schemas

Metaphors can help to realize mental models. Generally, a metaphor is a linguistic image that uses a term from a familiar source domain and applies it to an unknown or abstract target domain on the basis of an analogy. Metaphors are widely used in our daily communication, and also in human-computer interaction their application has a long success story. To make computers accessibly to non-expert users, the Apple Lisa introduced in 1984 a graphical user interface with “physical office metaphor” (later called desktop metaphor): icons represented documents, folders, waste baskets etc. and could be manipulated by clicking and dragging with a mouse (Smith et al. 1982). This idea was highly successful and still dominates our interaction with personal computers and desktop systems. Nevertheless, interaction techniques advanced and with the rise of tangible and gestural interaction novel easy to understand and to learn interactions need to be designed. Fishkin, for example, suggested to apply “metaphors by verb” and “metaphors by noun” when designing tangible user interfaces (Fishkin 2004). To design gestures in line of the understanding of natural interaction, it is important to explore when and how everyday interactions with materials and objects in our surroundings can guide gestural interaction, e.g., how metaphorical applications of material affordances can potentially guide gestural interaction.

A class of metaphors that are particularly relevant for tangible and gestural interaction are *embodied metaphors – metaphorical extensions of image schemas*. Based on Johnson (1987), Hurtienne and Israel (2007) present *image schemas* as “abstract representations of recurring dynamic patterns of bodily interactions that structure the way we understand the world” (Hurtienne and Israel 2007, p. 130). Image schemas were identified within linguistic studies (Johnson 1987) and compiled into lists that have been applied in embodied and tangible interaction design recently, e.g. (Hurtienne and Israel 2007), (Bakker et al. 2012). Image schemas are based on humans' sensory-

motor experiences and exist subconsciously (Hurtienne and Israel 2007). One example image schema (of approx. 30 to 40) is the image schema “IN-OUT”, which consists of a container and movements into or out of the container (cf., Bakker et al. 2012). From the beginning of their lives, humans experience actions based on this image schema, e.g. when putting food into a mouth or entering a room. Thus, they form the abstract image schemata “IN-OUT” subconsciously. Based on these experiences, humans unconsciously apply image schema metaphorically to abstract domains, e.g. when saying “I am in love” or “Let’s leave out some details” (Bakker et al. 2012, p. 434). These *metaphorical extensions of image schemas* are also called *embodied metaphors* (Lakeoff and Johnson 1980), as they are based upon bodily experiences. They are regarded as useful underlying theory when it comes to the design of tangible and embodied interaction where body movements and the manipulation of artifacts are used to control abstract functions. In order to find mappings that are easy to understand and to learn, UI designers have applied image schema and embodied metaphors, e.g., to the conceptual design of a tangible memories box (Hurtienne and Israel 2007), to map full-body movements (Antle et al. 2009) or for the manipulation of artifacts (Bakker et al. 2011) to control pitch, volume and tempo of music. As a starting point for patterns for tangible interaction Hurtienne and Israel (2007) introduce 7 clusters of image schemas: basic schemas, space, containments, identity, multiplicity, process, force, and attribute. In a user study, Hurtienne et al. (2009) conducted further research on how metaphorical extensions from the attribute image schema cluster can be applied in mappings for tangible interaction. For example, they took two lego bricks of the same size, one white one black, and asked participants, which one would better represent “happy” and which one would better represent “sad” (basing upon the image schema “BRIGHT-DARK” and its metaphorical extension “happy is bright - sad is dark”). They found the metaphorical extensions applied in many cases, e.g. for the given example, 87 percent of the participants mapped the white lego brick to happy and the dark one to sad. However, overall only approximately three fifth of the tested embodied metaphors were confirmed by at least 80 percent of the participants, which shows that not all metaphors work equally well and that the specific context and the presentation styles have important impacts.

2.4. Chapter Summary

This chapter covers the relevant HCI background for this work. First, in Section 2.1, we introduced embracing terminology such as *natural interaction*, *reality-based interaction*, or *embodied interaction*, and *interactive surfaces*. For understanding and designing user interfaces in these domains, a materials perspective matters. The case studies, in which we practically explored aspects of materiality for interaction and that will be presented later in Chapter 4, apply concepts of these fields. Furthermore, in Section 2.2 we focused on *gestural user interfaces* and *tangible user interfaces* as two central types of UIs within this work. Finally, to provide an overview on important concepts for designing interaction, we additionally introduced *mental models and mappings*, *constraints and affordances*, as well as *metaphors* in HCI in Section 2.3.

3. Materiality and Human-Computer Interaction: Themes and Framework

3.1. Material-Centered Themes in Human-Computer Interaction

This section gives an overview on the main discourses on material and materiality-related aspects within human-computer interaction, structured into eight themes (see Figure 3.1). These are not mutually exclusive but rather present different point of views and focus points. Some works could be regarded as examples for two or more of the themes, depending on how the focus is set. The themes help to shape, identify and analyze the topics of this emerging field. These eight themes are:

1. Conceptualizing Materiality and Material in HCI
2. Material-Focused Frameworks and Methods
3. The Computer as Material
4. Physical Materials for Interaction
5. Novel and Advanced Materials
6. Making, Craft, and Do-It-Yourself
7. Sustainable Interaction Design
8. Understanding the Roles of Materials in Practices

The first two themes are dedicated to material-centered theory and address what we can understand as material in the context of HCI as well as how novel frameworks can support a focus on materials and materiality in design and analysis (1. *Conceptualizing Material in HCI*, 2. *Material-Focused Frameworks and Methods*). As part of a material-centered practice in HCI, three themes are evolving. The first one *The Computer as Material* (theme 3) discusses software and hardware as materials, which leads to new insights into practices and novel design approaches. The second one, *Physical Materials for Interaction* (theme 4) explores properties and meanings of physical materials as part of user interfaces, among which are, for example, paper and fabrics, clay, or liquids. A third one, *Novel and Advanced Materials* (theme 5), extends the material canon in HCI by integrating new materials, for example smart materials that allow novel ways for sensing or actuation. The ongoing development of materials with novel properties in materials engineering provides many opportunities for HCI. Themes 6, *Making, Craft, and Do-It-Yourself* and 7 *Sustainable Interaction Design* are material-centered fields that currently mark growing fields in which material aspects play an important role. Last, theme 8 *Understanding*

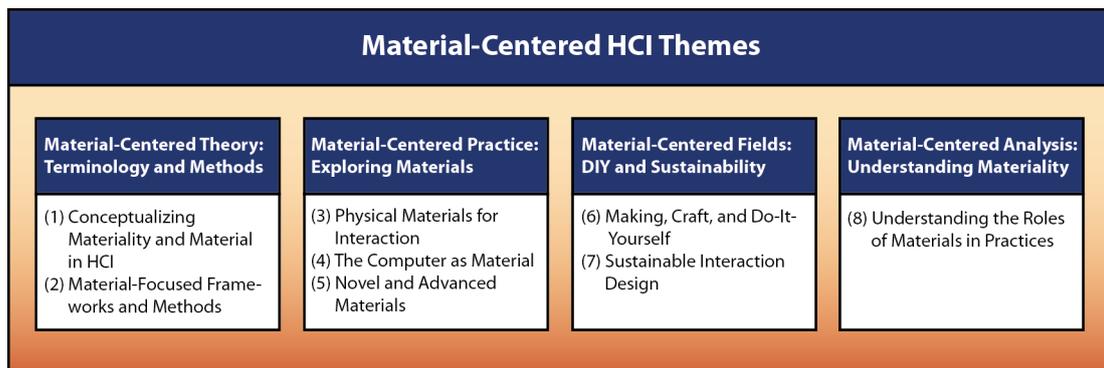


Figure 3.1.: Eight material-centered HCI themes. The themes frame different material discourses as part of a materials perspective on HCI and present the dedicated subtopics the results of this thesis contribute to.

the Roles of Materials in Practices covers material-centered analysis as part of human-computer interaction.

These eight themes were identified by a comprehensive literature review as well as based on experiences about ongoing research gathered through conferences and exhibitions. As the research field on materiality within HCI has evolved since I started my work in this area, some aspects of these eight themes can be similarly (to shorter extend) found in other overview publications recently published, for example in Wibergs “six approaches to the material turn” (Wiberg 2016) (namely: *new materials*, *computational expressivity*, *analogies to craft*, *new evaluation methods*, *computer as material*, and *materiality*). Three of the included publications of this thesis also cover selected aspects on *Physical Materials for Interaction* and *Making, Craft, and Do-It-Yourself* (Döring et al. 2009, 2012a, Döring 2014).

3.1.1. Conceptualizing Materiality and Material in HCI

The notions of material(s) and materiality have been widely used within HCI in recent years. Nevertheless, what is understood by a material and materiality varies, not only within human-computer interaction, but also in other fields like materials engineering, material culture or anthropology. Addressing and analyzing the terms from an interaction design perspective, Fuchsberger and colleagues conclude that “... materials is what we work with, materiality is what emerges through design or usage.” (Fuchsberger et al. 2014b, p. 4). Generally, throughout different disciplines, the term “materiality” is used in a more abstract and scholarly way than “material”, which traditionally refers to “physical substance” (Vallgård and Redström 2007, p. 514) or the matter things are made of, while materiality is used to denote the whole of the research field itself; cf., Fuchsberger et al.: “Similar to the distinction between method and methodology, we understand materiality as the theoretical discourse about materials” (Fuchsberger et al. 2013, p. 2854). This generally subsumes a number of diverse themes and perspectives, of which I sketch 8 themes in this work. Gross, for example, focuses on three dominating views on materiality in HCI: “tangi-

ble user interfaces” (physical materials), “computation as materials” (a metaphysical materiality), and “craft and/as HCI (materiality as tradition communication)” (Gross et al. 2014). Materiality as term has been used and discussed broadly within social sciences and material culture. The social anthropologist Ingold, for example, compared different aspects scholars refer to when they use the term materiality and concluded: “In every case, there seem to be two sides to materiality. On one side is the raw physicality of the world’s ‘material character’; on the other side is the socially and historically situated agency of human beings who, in appropriating this physicality for their purposes, are alleged to project upon it both design and meaning in the conversion of naturally given raw material into the finished forms of artefacts.” (Ingold 2013, p. 27). It is especially this second aspect that has recently been linked to by HCI researchers in order to argue for establishing a materiality focus in human-computer interaction, e.g., by putting “emphasis on the meaning and value of a material artifact doing more in reality than what it is initially designed for” (Jung and Stolterman 2012, p. 649). Others, like Dourish and Mazmanian (2011) and Blanchette (2011), are especially interested in the materiality of bits and discuss the “different potentialities and different constraints” (Dourish and Mazmanian 2011, p. 16) the material natures of digital representations provide. Their notion of “materiality” also builds on the works of social scientists and anthropologists. Dourish and Mazmanian argue that materiality goes beyond *material-ness*: “we want to understand the particular material properties of these forms and their consequences for how people encounter, use, and transform them” (Dourish and Mazmanian 2011, p. 4). In their special issue on material interactions in the *Personal and Ubiquitous Computing* journal 2014 Wiberg and colleagues aim to “establish “materiality” as a theoretical perspective and as a methodological lens” (Wiberg et al. 2014, p. 2) in HCI. Wiberg furthermore suggests a “methodology for materiality” that “follows the simple dialectic tradition in design to work back and forth between materials and materiality, details and texture” (Wiberg 2014, p. 626). Thus, for Wiberg, materiality in HCI denotes an analytical and holistic view on materials as part of interaction, incorporating aspects of composition, experience, and meaning. In a later publication, Wiberg presents a “materiality of interaction” perspective that demands for three future work strengths through a material lens: “the development of (1) unique form-giving practices, (2) artistic and research-driven accounts of interaction, and (3) systematic knowledge production” (Wiberg 2016, p. 4). This broader view on materiality includes next to the analytical lens as well aspects of design and making.

After all, the term “materiality” is used very diversely in human-computer interaction (see also Wiberg 2016, Giaccardi and Karana 2015) and can be used as an umbrella term, depicting all aspects materials in interaction design relate to. Drawing on anthropology and social sciences, this includes aspects of meaning and understanding how they constrain and shape interactions and further practices. In this sense, it is often used as an analytical lens. Furthermore, with influences from art, architecture and design, materiality in HCI also subsumes aspects related to design and making, which I would regard as the constructive lens of materiality.

Researchers interested in materials of user interfaces often focus on very different aspects, ranging from *physical materials*, to *intangible materials*, to *hybrid materials* or *computational composites* to *computational and digital materials*. When discussing the “material move” in HCI, for example, Fernaeus and Sundström (2012) discuss three material-focused design challenges, namely “affordances of hardware and casings” (i.e., physical materials), “experiential proper-

ties of different software solutions” (i.e., digital materials), and “material properties of sensors, radio-signals, and electricity” (i.e., computational materials). Especially in the research area of tangible user interfaces, *physical materials* play a novel and much more important role for the user interface (Ishii and Ullmer 1997): e.g., aspects of shape are used to afford or constrain certain actions, the materials themselves present data, preferably in a meaningful way, or materials are used to evoke emotional response. In this context, the diversity of physical materials and shapes increased: e.g., wood, textiles, or paper were used as physical materials for interaction (see also Subsection 3.1.3). Next to physical materials that are tangible, recently in many works also *intangible materials* like air, scent, or light are used as an interaction material. Kwon and colleagues explored the related design space of tangible and intangible materials together with *computational materials* (Kwon et al. 2014). They use the latter term, *computational materials*, synonymously to *immaterial* or *digital material*, referring “to bits and bytes or any digital information that begins with a calculation process of zeros and ones” (Kwon et al. 2014, p. 654). Kwon et al. also regard hardware and sensors as computational material, as “their physical characteristics only protect the computing process” (Kwon et al. 2014, p. 654). Perceiving computers as material has been introduced by Vallgård and Redström (2007), who argued that computers could be seen as a design material with specified substance, structure, surface and properties (and in this sense similar to more traditional materials). Nevertheless, computational properties cannot be exploited without combining the computer with other materials. This combination is what Vallgård and Redström called a *computational composite* (for further information see Subsection 3.1.4). Another term that is often used when digital and physical materials are merged is *hybrid*. E.g., Crabtree and Rodden (2008) speak of evolving “hybrid ecologies” that merge physical and digital environments. Among the central themes when discussing computational materials are novel properties such as temporal form (Vallgård et al. 2015) and how these can be experienced (Sundström et al. 2011). While the terms *computational materials* and *digital or virtual materials* often are used synonymously in the literature, Fuchsberger et al. suggested to use computational material for what “is needed to creating a design’s temporal form” (Fuchsberger et al. 2014a, p. 452) and digital material for “the information that is generated, collected, managed, distributed, and employed” (Fuchsberger et al. 2014a, p. 452).

This overview shows that what researchers regard as materials in HCI and what aspects they are interested in can span from the physical to the digital with different instantiations in between. At the same time, how the related terminology is used differs throughout the literature. In Subsection 3.2.1 I will address how the terminology is used in this work. Additionally, this work contributes to the theme of material-related terminology by the introduction and definition of the term *ephemeral user interface* (see Section 4.3).

3.1.2. Material-Focused Frameworks and Methods

Within human-computer interaction, recently some first frameworks and methods have been designed and explored to better understand how materials unfold in interaction design and user interfaces. These vary in their orientation to either support a *material-focused reflection* (ana-

lytic lens) or a *material-focused design process* (constructive lens) as well as in their scope, i.e., whether they take a rather *holistic approach* or address *dedicated material aspects*.

Wiberg, for example, proposed a high-level and comprehensive approach to support a material-centered analysis and described four important dimensions as part of a *methodology for material-centered interaction design research* (Wiberg 2014, p. 625): i.e., *materials, details, texture, wholeness*. Inspired by Donald Schön's position on working closely and in a reflective way with materials, allowing them to "talk back to the designer" (Schön 1984), Wiberg's methodology aims to provide a "a guiding system that can help in guiding what to look for and what to pay attention to at different stages of a research process." (Wiberg 2014, p. 628). Its central idea is to work back and fourth between the four different levels of analysis, whereas specific research questions and methods are dedicated to each. The focus on *materials*, for example, includes exploring the properties and the character of a material, which leads to an understanding about a materials's limitations and potentials. Second, the level of *wholeness* focuses on how materials unfold as part of compositions, how these are experienced and interpreted, thus, on the meaning of materials, taking the context into consideration. Third, *texture* is a relational concept that embraces questions around how material properties are communicated through a material surface, e.g., how the visual and tactile appearance is or whether this appearance is authentic. Last, *attention to details* marks a level of analysis that focuses on supposed small aspects of the design and of the implementation that still shape the overall aesthetics and quality of the composition to a large degree. Overall, all of the four levels of this proposed methodological structure demand for dedicated methods.

Another comprehensive and high-level approach that in this case addresses aspects of reflection as well as of design has been proposed by Jung and Stolterman (Jung and Stolterman 2012), who argue for a *form-driven interaction design research approach* as opposed to functionality-driven user-centered approaches. The authors propose *form* and *materiality* as lenses to support the creation and critique of interactive artifacts. They argue that form did not play a role in the beginning of computing, but gets increasingly important as at the same time also more complex physical and digital components merge into interactive artifacts in our surrounding. Within *form*, the authors furthermore describe three perspectives: *material, shape, and making*. The material perspective addresses the materials – digital and physical – used to create forms of interactive artifacts. The shape perspective addresses the appearance of the form and focuses on questions like how to couple shape and meaning or how to apply product semantics to shape. Third, the making perspective addresses issues around the creation of digital artifacts and the challenges of shared understandings of involved actors. Due to the different disciplines involved and the complexity of aspects around interactive artifacts, making differs from traditional crafting in design, where form is not separated from function. Within HCI, toolkits give people with different backgrounds novel possibilities for a participation in the design process. Within the second lens, *materiality*, which addresses a higher level reflection on the relationship between people and material artifacts, Jung and Stolterman discuss *meaning* and *material ecology* as two important aspects. While meaning deals with the "relationship between people and things from cultural and socio-technological contexts" (Jung and Stolterman 2012, p. 649), material ecology focuses on "connected aspects among multiple artifacts in use" and discusses how they interact. Based on this proposed model they suggest three themes as part of a form-driven approach for interaction

design: first, *form as experiment*, second, *form as intention*, and third, *form as medium*. Form as experiment characterizes the exploration of different shapes, materials and textures (e.g., through approaches as “material probe” see Subsection 3.1.3) to investigate their potentials for interaction design. The authors have the opinion that, due to the holistic experiences evoked by materials, measuring the effect of single variables would not make sense. The second theme, form as intention, addresses the designers’ intention, which normally is influenced by a variety of factors. In order to support it, “a contextually, historically, and disciplinary grounded understanding of form is in demand” (Jung and Stolterman 2012, p. 652) and this could be supported by research from material culture or examples from art and design for example. The last theme, form as medium, focuses on re-making and cognitive or embodied user engagement with artifacts. Users appropriate objects for their own purposes, they sometimes even modify them or – especially with novel tools and toolkits – build their own artifacts, as observed in the growing DIY and maker scene for example.

Taking a hermeneutic approach, Giaccardi and Karana (2015) focused on experiential qualities and presented an analytic *framework on materials experiences*. This consists of the three interacting nodes *material*, *people* and *practices* and the relationships between these (called *encounters*, *performances* and *collaborations*). The authors stress that these relationships are dynamic and embedded in contexts and highlight that a holistic understanding about how these entities relate, in the moment and over time, build the basis for their work. Based on this they discuss material experiences on four different levels: on the *sensorial level*, the *interpretive level*, the *affective level* and the *performative level*, whereas all levels affect each other. The sensorial level addresses how materials are experienced through senses, i.e., through touch, vision, smell, sound and taste. Second, the interpretive level encompasses the situated associations and meanings people ascribe to materials. Third, the affective level focuses on emotions evoked by materials. And last, the authors describe a performative level that describes the performances established around the materials and how the materials mediate and affect these. A discussion and analysis of these experiential levels offers structured insights into how materials unfold as part of user interfaces, i.e. how they “shape ways of doing [...] and practice” (Giaccardi and Karana 2015). Giaccardi and Karana apply their framework to analyze a number of design cases and discuss what they call “active” and “broken patterns”: notions that relate to whether the selected materials support intended practices or not as part of the performative level. Overall, with their work the authors provide a structure that helps to better understand how materials take effect on different experiential levels.

Fuchsberger et al. published a *materiality-centered approach* to describe and better understand relations between users and objects combining human-oriented perspectives and artifact-oriented perspectives (Fuchsberger et al. 2014a). Based on Latour’s Actor Network Theory (ANT) (Latour 2007) that considers artifacts and humans as actors in a network, the authors built an approach to model networks on the basis of data gathered from contextual inquiries in application contexts. In their networks, Fuchsberger et al. apply the concept of “monads” (Latour et al. 2012), specific entry points to networks that shape points of views to all other entities and that are followed along their traces. In order to combine a human-oriented perspective and an artifact-oriented perspective, the authors explored these as different entry points, building different monadological approaches. To give an example, the authors conducted observations and contextual inquiries in

a factory with the goal to analyze the use of paper and electronic control sheets in a cleanroom and afterwards modeled the attributes of four different monads in form of networks. The different monads were: a human-oriented perspective to paper control sheets, an artifact-oriented perspective to paper control sheets, a human-oriented perspective to electronic control sheets, and an artifact-oriented perspective to electronic control sheets. This analysis revealed that different entities were visible depending on the perspective. For instance, aspects of the paper control sheet creation and archiving did only appear in the artifact-oriented perspective, not in the human-centered perspective that followed the operators' actions in the cleanroom. Furthermore the analysis revealed that taking an artifact-oriented perspective on the electronic control sheets required a focus on the digital information as an own actor that needs physical representations to be accessible. Overall, this approach allows to integrate user-centered and artifact-centered perspectives into one model and enhances earlier approaches by a materiality view.

Karana et al. proposed a *material-driven design method* (MDD) that starts from a material and addresses functional as well as experiential qualities from a product design perspective (Karana et al. 2015). The method is intended to support three different scenarios: “designing with a well-known material, a fully developed new material, a semi-developed new material” (Karana et al. 2015, p. 48). The scenarios differ in their degree of material availability for exploration as well as of established material profiles and meanings. The method itself consists of four steps. The first step focuses on *understanding the material*, which includes a technical as well as experiential characterization of the material, e.g., by tinkering with the material, through material benchmarking or conducting user studies. The second step of the method targets at creating a *materials experience vision* and involves a reflection upon and condensation of the insights from step 1. Ideally, based on this, the designer formulates how the experiential qualities of the material would be and in what context it could be applied. Alternatively, another step can be integrated, in which findings are clustered and structured according to the *vision in product design* (Hekkert and van Dijk 2011) method to support envisioning the materials experience. In a third step, *materials experience patterns* are manifested by conducting user studies. These follow the *meaning driven materials selection method* (Karana and Hekkert 2010). In this, participants are asked to select a material that they think fit a certain attribute (e.g., that is modern or feminine) and to provide a picture of the material. Furthermore, they are asked to explain their choice and rate the material on sensorial scales. Based on an evaluation of the results, the designer formulates a materials experience pattern, i.e., the relationships between the materials properties and explored meanings. Finally, the last step of the method focuses on the creation of *material or product concepts*, which involves practical design tasks with the material and further material tinkering and testing. Depending on how far the initial material is developed this step can reach from manipulating sensorial qualities to building novel composite materials. The resulting product concepts should be tested in the lab and the field as well as evaluated against the earlier formulated materials experience vision.

Two further relevant methods, both supporting design tasks, are the *the material probe method* by Jung and Stolterman (2011), which focuses on users' associations regarding physical materials, and *inspirational bits* by Sundström et al. (2011), which addresses experiencing properties of computational materials. I will present these two methods in the subsections on physical materials and on the computer as material, respectively.

This thesis contributes to this emerging body of works on material-focused frameworks and methods by providing *a framework to inspire and understand how material aspects shape interaction* (see Section 3.2). As part of this, I present *the interaction material profile*, a structural approach to understand and inspire how material aspects unfold in user interfaces (see Subsection 3.2.2) and *the physicality representation spectrum*, a schema that addresses the spectrum how physical materials are represented within user interfaces (see Subsection 3.2.3). Furthermore, we developed *a design space for ephemeral user interfaces* (see Subsection 4.3.1).

3.1.3. Physical Materials for Interaction

While in classical design disciplines the discussion of physical materials have a long tradition (cf., Manzini 1989), within HCI it started especially with the research area of tangible user interfaces that physical materials were brought into the focus. Be it as representations of digital data, as manipulation handles or as surrounding elements of a user interface, the physical materials need to fit to the data, the manipulation task, the user interface and the context on many levels. This opens up a new research space that explored different and often unconventional materials, investigated in user studies how properties and connotations of these materials unfold as part of prototypes, and started to question how the material selection can be supported more systematically. Next to the more traditional materials, like plastics and wood for instance, materials with a strong focus on diversity in tactile feedback such as paper (e.g., Kaplan and Jermann 2010, Cuendet et al. 2011, Qi and Buechley 2010, Coelho et al. 2009, Buechley et al. 2009, Saul et al. 2010), fabrics (e.g., Berzowska and Skorobogatiy 2010, Nack et al. 2007), or clay (e.g., Piper et al. 2002, Reed 2009) were applied within user interfaces. Our work on ephemeral user interfaces reveals how the material canon even increasingly expands and includes fog, liquids such as water, food, or plants. While many early concerns about tangible objects for interaction focused around mapping and affordances (see Section 2.3), some researchers started to put aesthetics and experiential qualities of materials and their surfaces into the focus (e.g., Regier 2007, Schiphorst 2009). Davis et al. (2013), for instance, investigated how the visual perception of selected textile patterns triggered emotional reactions and assessed arousal, valence and mood. While traditional HCI design approaches usually start from a use case and its requirements, a valuable alternative approach that might lead to more innovative and material-driven results could also start a design from a given physical material. Schmid et al. (2013) explored this with the example of glass as interaction material. They carefully analyzed its potentials and challenges and tinkered with the material in hands-on workshops, which led to a number of prototypes and insights into the design space for glass as interaction material. Recently, a dedicated research focus evolved on data physicalization (cf., Jansen 2014), an area that specifically investigates how physical material properties can encode data.

In the following, I will highlight some of the explorations and studies that started to systematically investigate selected physical material aspects for interaction. When Kaltenbrunner and colleagues, for example, developed an early version of the reactable (see also Subsection 2.2.2), they explored different tangible object types as interaction handles and looked at, what they called, “haptic encoding” (Kaltenbrunner et al. 2004). For example, they represented different

object types (e.g., generators, processors, controllers, mixers) by different shapes and tried out different sizes as well as flat and cubic objects. Additionally, the authors explored different surface textures (e.g., created through lasercutting or by attaching felt or sandpaper) and materials (i.e., plastics and wood), aiming for a good mapping to the properties of related sounding objects. Despite these early explorations, today the resulting set of handles are all of the same material with the same smooth surface. The digital object types are encoded by distinct shapes and imprinted icons. Another early study that investigated different physical properties for interaction is Sheridan's and Kortuem's study on 6 different cubes that are intended to be used for input. Participants were exposed to 6 different cube or cube-similar shapes, varying in size, material, surface texture, weight, etc. Subsequently, they were asked to pick a cube and manipulate it to perform an imaginary control mechanism. This way, the authors collected a number of typical manipulations afforded by the different objects (e.g., malleable cubes afforded rolling and squeezing, large cubes afforded flipping, cubes with beads inside afforded shaking) and derived, for example, general preferences for cubes with multi-sensory feedback and some degree of weight.

Recently, Petrelli et al. (2016) conducted a systematic study on how interactive tangible objects, each varying in one feature, are perceived by users. The authors designed 32 three-dimensional objects of which each presented a unique combination of four characteristics: shape (cube or sphere), material (fabric or plastic), size (7.5 cm or 15 cm) and behaviour (light, sound, vibration, or no behaviour). All objects had a white color and were put separately under boxes that had to be lifted during the experiment in order to avoid any visual impressions before users could touch the object. In a first study, 175 users were asked to experience and describe their impression of the objects. Based on the adjectives used in these descriptions, seven dimensions of object impressions were derived (i.e., interesting, comfortable, playful, surprising, pleasant, special, and relaxing) and subsequently used in a second study. This time, 486 new participants, were asked to experience the objects (again, one at a time, beforehand hidden under a box) and to rate them regarding the seven dimensions. The overall results reveal a number of insights, for example that users rate spheres more positively than cubes and the fabric objects more positive than the plastic ones. Small objects were regarded as more playful, and from the behaviors, vibration was found the most positive. The participants also generally preferred interactive objects over non-interactive ones. Some of these findings confirm previous findings from psychology, e.g., that round objects generally are preferred over sharp edges, that haptic exploration outreaches other senses, or that a reacting object fosters a stronger psychological connection. The preference for fabrics also might indicate a preference for the handmade and natural. The authors even conclude that "this has significant implications for the design of tangible as it suggests that the use of the natural material is likely to lead to more positive psychological reactions to such products" (Petrelli et al. 2016, p. 106).

To better understand how children experience touching different artifacts, Kierkels and van den Hoven conducted a user study on "children's haptic experiences of tangible artifacts varying in hardness" (Kierkels and Van Den Hoven 2008). For their study they designed four objects identical in shape with different degrees of hardness (from very soft to very hard). 30 children in the age of 10 to 13 years were asked to grasp them with both hands inside a "blind box", such that they could not see the objects. After touching all objects, the children were asked to chose fitting adjectives from 20 pairs of adjectives and their antonyms (e.g., active - inactive; adventurous -

timid). Furthermore the children were asked to order the objects regarding to their degrees of hardness. Out of the 20 pairs of adjectives, for 15 pairs a clear trend could be found, regarding which of the adjectives fit to a soft and which of the adjectives fit to a hard object (e.g., the softer an object the more cute, funnier, or warmer it was perceived; and the harder an object, the more brutal, serious or cold it was perceived). This list presents a starting point for how to relate interface elements through their degrees of hardness to specific adjectives, a result that could be applied to the design of tangible user interfaces for hybrid games.

In a more recent study, Seo et al. (2015) focused on material significance of tangibles for children and developed an interactive game, in which physical stamps made from different materials (i.e., plastic, wood, silicone and felt) could be associated to digital graphics from different categories (i.e., animals, fruits, musical instruments and clothing) or to different colors. In the experiment, 19 kids were first asked to associate the stamps to a given set of digital representations and afterwards to recall these associations during only being exposed to the stamps. The results reveal that certain materials seem to fit certain domains better, e.g., the kids associated wood most likely to musical instruments, felt to clothes, and both silicone and plastic to animals or fruits. For the colors, no significant associations could be found. During the recall task, the children remembered the associations for the soft materials, silicone and felt, first more often. Generally, during a free drawing task, most tended to prefer the silicone stamp first, even when they could not recall any associations, which indicates a general preference for the material. From the study can be learnt that apparently certain materials work better for certain associations, and that semantic associations and as well the material feel play a role for this.

Further interesting studies on using dedicated material aspects more systematically for interaction were conducted by Hurtienne and colleagues (e.g., Hurtienne et al. 2009, Löffler et al. 2016, Hurtienne and Meschke 2016) as well as Antle and colleagues (e.g., Antle et al. 2009, Macaranas et al. 2012), who applied embodied metaphors and image schemas to human-computer interaction (as already briefly introduced in Subsection 2.3.3). Although their focus is not restricted to the materials but also includes spatial aspects for example, these studies derive a number of implications for material aspects of tangible user interfaces. They show how for pairs of objects with different sizes, weights, shapes, stiffnesses, textures, colors or temperatures the single objects are often more likely related in the same way to opposed pairs of associations, values or emotions. For example, given a small and a large object of the same style, the small one is usually rather mapped to less and insignificant, the big one to more and significant. A warm object is more likely to be mapped to emotional, a cold one to unemotional (Hurtienne et al. 2009). A hard object is rather regarded as stressful, while a soft one relates to relaxing. A rough surface is rather associated to the attributes impolite, unpleasant and problematic, while smooth surface is more likely to be mapped to the opposite (Macaranas et al. 2012).

To support understanding and addressing non-functional user desires regarding material qualities of interactive artifacts in interaction design, Jung and Stolterman (2011) propose a user-centered design approach called “material probes”. The material probe approach is inspired by the cultural probe method invented by Gaver and colleagues (Gaver et al. 1999) and takes place in form of a user study session with participants. A session is divided into three parts. In the first part, the participants are asked to tell stories about physical objects they like or dislike due to their

materials' properties and to describe experiences with these objects. In the second part, participants get a set of material samples to play with. The set consists of materials like felt, rubber or plastics spanning a range of different physical properties "i.e. soft, hard, shiny, warm" (Jung and Stolterman 2011, p. 154) including different shapes. Participants are asked to select 2-3 samples they especially like or dislike and to explain and justify their choice. In the third part, these findings are compared to experiences with digital artifacts. Participants are asked to describe digital devices they frequently use and relate their "experiential qualities" (Jung and Stolterman 2011, p. 154) to the beforehand selected material samples. Based on this, a discussion is started on how the digital devices could be improved regarding material qualities. The authors conducted three material probe sessions with 15 participants in total, all with a background in HCI. In these sessions the approach revealed that people care about material characteristics and that physical material could indeed be used for interactive artifacts to improve its functionality beyond casings or pure decoration (e.g., "a bouncy phone", "a smelly phone" or "an encouraging keyboard" Jung and Stolterman 2011, p. 155). Furthermore, the approach was well suited to put a focus on understanding and using material qualities for interactive artifacts starting from physical materials. The authors found three directions this could lead to: material simulation (emulate material characteristics digitally), material expression (create more visible forms for better affordances) and material exploration (new concepts for user interfaces relying on its materials). Overall, this approach does not claim to provide universal design guidelines regarding material, but offers a procedure to structurally address qualities of physical materials for the design of digital artifacts.

Häkikilä et al. (2015) applied this material probe approach in a varied form to natural elements as interaction materials, i.e. stone, water, ice, sand, wind, fire, and soap bubbles. In their study, 16 participants were exposed to probes of the seven materials and asked a number of questions, e.g., to express associations, to rate them regarding certain criteria, to relate the materials to digital artifacts and to activities, and to select the best describing attributes from a list. To most participants, water was the favorite material. Regarding "overall preference" water was closely followed by soap bubbles. Other assessments by the participants were, for instance, that fire and wind are the least controllable materials, soap bubbles the most fun, water and ice were regarded as calm, and stones as serious. Nevertheless, some of the results from the ratings and the list of attribute pairs were to some extent contradictory. This diversity of individual assessments also became clear in the associations between materials and digital artifacts as well as materials and activities, which in most cases, did not reveal clear overall preferences. Exceptions were, for instance, that sand was associated to "organizing files" by the majority and fire was related to notifications (e.g., remember meeting or shopping). Many also associated wind and soap bubbles to "browsing pictures". So overall, this study explored the field of taking natural materials for interaction. Nevertheless, the results also demonstrate that it is difficult to assess the materials by themselves without embedding them into an application context.

Especially when we want to design meaningful interactions, the practices and the context these are embedded in are of major importance. Giaccardi, for example, addressed this and discussed the "things we value" and how heritage practices can play a role for interaction design (Giaccardi 2011). Petrelli et al. have presented approaches to integrate "material and digital" in cultural heritage with the goal "to put the physical back at the center of the cultural heritage experience"

(Petrelli et al. 2013, p. 60), highlighting material aspects such as “aura” and authenticity. The theme *Understanding the Roles of Materials in Practices* (see Subsection 3.1.8) covers studies that investigate the value and meanings of materials in order to derive insights for HCI. Other interesting and relevant works on understanding properties and meanings of physical materials for design stem from product design. Van Kesteren et al. (2007), for example, designed tools for including user interaction in materials selection. Sonneveld (2010) explored the meaning of non-functional touch and Karana (2010) conducted research on the meanings of materials for design. A recent compilation and overview over many aspects around material experience for product design has been published by Karana et al. (2014). Within this, the authors also mention potentials to apply Kansei Engineering (Schütte et al. 2008) to product development, in order to better understand how users’ experiences and attributes of a product are related. Although it should not be the only approach, this path could also be interesting to integrate material aspects into disciplines as computer science more systematically.

In our case studies on gestural, tangible, and ephemeral user interfaces exploring physical materials for interaction has been a major focus. Thus, we contribute with our work to this theme for example by extending the classical canon of physical materials for interaction through ephemeral user interfaces (see Section 4.3), which also incorporate unconventional and natural materials in different state of matters, by an in-depth exploration on soap bubbles for interaction (see Subsection 4.3.2), by comparing wooden tools to digital tools in a tabletop-based group application (see Subsection 4.2.2) or by designing and exploring an end-user toolkit for tangible devices that consists of a number of classical craft materials like paper, foam boards, and stickers (see Subsection 4.2.1).

3.1.4. The Computer as Material

As introduced in Subsection 3.1.1, one of the driving factors for materiality research in HCI is to regard the computer or the digital as material. There are several reasons for this. From an interaction design perspective, it has been acknowledged that it is important to understand hardware and software elements to be able to use them similarly as traditional design materials, i.e., as physical materials, are used. This involves tinkering and “starting a conversation with the materials” (Schön 1984) with the goal to understand and experience how the digital and computational materials can influence the final outcome, how their properties take effect in the resulting hybrid artifact. This is also linked to taking a craft approach in interaction design (see Subsection 3.1.6). Nevertheless, digital and computational materials are very difficult to experience as they need to be coupled to physical materials to be perceptible (Kirschenbaum et al. 2009, Dourish and Mazmanian 2011, Blanchette 2011, Fuchsberger et al. 2014b). Furthermore, their properties change over time, a fact that makes it difficult to anticipate the behavior and understand the temporal form (Fernaes and Sundström 2012, Vallgård et al. 2015), not only for designers but also for programmers. Nevertheless, the involved hardware and software shape to a large degree the behavior, look and feel of hybrid artifacts. Often, software and hardware parts are chosen for pragmatic reasons like easy availability, although it has been shown that they fundamentally influence the overall experience of the outcome as well as the evolving practices around it (cf., Bergmark and

Fernaes 2016). Understanding hardware and software as materials in interaction design reveals this issue and explores ways to better understand how these act as part of hybrid artifacts, e.g., by providing a material concept (Vallgård and Redström 2007) or by designing methods for material explorations (Sundström et al. 2011). Fernaeus and Sundström (2012) furthermore see “methods for communicating material properties and possibilities” as well as a “practical application of knowledge gained from material explorations” as important activities to support. Overall, within the theme *the computer as material* three strands are evolving: first, *computational composites*, second, *hardware as material*, and third, *software as material*.

Due to the lack of concepts and terminology to describe the combined usage of computation and traditional design materials like wood or textiles in interaction design and HCI Vallgård and Redström introduce the term *computational composite* (Vallgård and Redström 2007). They argue that computational technology could be seen as a material in the design process and underpin this concept by describing categories that typically are used to characterize a traditional material as well: *the substance*, *the structure*, *the surface* and *the properties* of the material “computer”. The *substance* of computational material can be seen as software and hardware. While hardware normally is regarded as being physical per se, this is unusual for software. Nevertheless, Vallgård and Redström argue for seeing both as physical (as the software is stored or executed for example) and therefore argue that computers can be regarded as complex substances (that have a “higher threshold” as they cannot be physically cut in half as other materials). The *structure* of computers consists of all the parts that can be found inside. The further we zoom into this structure, the more complex it gets. On a physical scale, the structure can be described as CPU, memory, buses and I/O devices; but of course, the CPU can be even further described by its components. Part of a computer’s structure, that is important for the properties of the computer, is also energy, represented as different voltage levels in the circuits, that form the current state. The *surface* of the computers is constituted by the input and output streams, i.e., the streams of discrete voltage levels that can be interpreted or are delivered as output. The authors describe the output stream as “the expressive side of the material” (Vallgård and Redström 2007, p. 517) and the input stream as the “possibility of moderating expression”. These options for interaction make a computer interesting as design material. Last, the *properties* of computers can be seen on different levels of abstractions from voltage levels to computations. If the computer is regarded as a single material, its property is only the “abstract ability to compute” (Vallgård and Redström 2007, p. 517). Only when combined with other materials, a computer can control mechanical or optical properties. Thus, “the computer needs to be combined to other materials for the computation to have an impact” (Vallgård and Redström 2007, p. 517); these combined materials are called “computational composites” and offer novel combinations of digital computations together with “tensile properties, optical properties, electrical properties, thermal properties and insulation, acoustic properties, deformations, deterioration, appearance and so forth” (Vallgård and Redström 2007, p. 517). Similar to other composites in materials science, e.g., aluminum, which gets its strength only through alloys with other metals, computational composites are created to enhance a certain material property or to get a set of novel properties. The *properties of computational composites* are computations, “events that can happen conditioned by a set of data and an algorithm” (Vallgård and Redström 2007, p. 517), which enable and control a transition from one state to another. These transitions can be triggered “with both algorithm(s) and data set predetermined”, “with only the algorithm(s) predetermined, and the data set collected dynami-

cally” or “with a predetermined offset of conditions that changes dynamically, for instance based a dynamically collected set of data” (Vallgård and Redström 2007, p.517). To describe the *structure of computational composites* Vallgård and Redström introduce two metaphors for the surface of the material: *front* and *rear*. The front of a computational composite handles the output the computation generates and “translates [it] to a transition towards a new state in the composite” (Vallgård and Redström 2007, p. 518). On the other hand, the rear of a computational composite depicts the access to the input stream, i.e., algorithm(s) and data. Example computational composites are computational textiles, computational concrete, or computational tensegrity. Overall, the authors provide a useful vocabulary that address the increasing interweaving of computers and physical materials.

While designers usually explore the properties of traditional materials early on in the design process to better understand a material’s qualities and to get inspired by its usage for a product, in the design process of interactive products the properties of the potential electronic parts and software are usually not directly explored, although their qualities often are not really known by many members of a design team. To make it worse, the qualities of digital materials like hard- and software often are harder to “grasp” as they are more complex due to changing properties regarding space and time. Technology parts often are seen as “black boxes” that are chosen without experiencing how they work, in many cases integrated at a late stage in the design process. Especially for designers, the creation of hard- and software often is too complex. All these aspects lead to a situation, where the designer’s essential “conversation with the material” (Schön 1984) including a “reflection-in-action” and “reflection-on-action” is not possible. To change this, several researchers have worked on tools, toolkits and techniques to facilitate the use of hardware and software as a design materials.

Bdeir (2009) for example took the perspective of taking *electronics as material* and presented LittleBits, a hardware toolkit that provides aesthetically appealing pre-assembled tiny circuit boards that can be easily connected by magnets in order to prototype interactive systems, without the need of detailed electronic knowledge. With LittleBits, Bdeir and her colleagues have the goal to facilitate that electronics are used earlier in the design process and that they are used by a broad variety of users beyond experts. Integrating interactive functions should be as easy as adding or shaping physical materials. Among the intended broader goals of the toolkit are a “democratization of technology” and a “demystification of electronics”. Today, LittleBits are commercially available, e.g., as an educational toy toolkit for kids. Mellis and his colleagues also took the perspective of regarding “microcontrollers as material” with the goal of “lowering barriers to entry” (Mellis et al. 2013b, p. 88), but presented a different approach. Instead of providing ready-to-use high-level modules and building blocks as in typical toolkits, they took an “untookit approach”: while providing users with small bare microcontrollers together with an accessible toolchain including software parts, their approach is based on the open integration of diverse existing craft materials and techniques, e.g., by drawing paper-based circuits with conductive ink. This “craft approach to technology” (see also Subsection 3.1.6) has, amongst others, the advantages of providing widely unrestricted form factors, of being low-priced and of being based upon familiar craft materials and techniques.

Sundström et al. (2011) presented “Inspirational Bits”, small playful applications to explore the properties of specific electronic parts. Inspirational Bits allow to integrate the direct experience of the properties of electronic materials early in the design process and thus also support a common understanding of the potentials and limitations of a technology and the collaboration in interdisciplinary design teams. Among the example technologies Sundström and colleagues realized and tested in the form of inspirational bits are bluetooth, RFID, accelerometers, wireless sensor networks and Radio. For example, to explore the properties of bluetooth, the team developed two “Bits”: BluePete and BTScore. In BluePete, participants could explore within which distances bluetooth connection can be established, how connections can be made and how data can be exchanged by running around with mobile phones in either listening or searching mode. When one listening device got close enough to a phone searching for a bluetooth connection, a picture of BluePete is transmitted to the phone. The goal of the game was to move around without getting BluePete displayed on the phone. In BTScore players collected scores when connections to other devices were established. Both “bits” were quickly built and could be explored in a game style, very embodied, by approaching other players. Overall, the authors found that the inspirational bits helped design teams to develop ideas that were “more grounded in the material” (Sundström et al. 2011, p. 1564).

The importance of regarding *software as design material* was emphasized by Ozenc et al. (2010). Among major obstacles for designers in current software development is that the idea how an interaction should be designed needs to be ready before it is realized, rather than allowing an iterative, exploratory approach that allow reflection based on “boundary objects” (Star 2005). Based on two participatory design workshops they propose the need for a new tool that supports refinement and communication of new interaction ideas by, for instance, providing video recordings of suggested “physicality, motion and interaction” (Ozenc et al. 2010, p. 2521). More recently, Lindell (2014) analyzed the “epistemology of modern programming” and conducted a study among programmers that revealed how they describe code as material. The author found different categories, such as “mastery”, “learning” and “explorative”, that discuss code as material and infers from this to see programming as a craft, relating to the concept of craftsmanship. Taking a rather philosophical perspective, Trogemann (2010) wrote about outdated material understandings that separate between the spiritual, immaterial and sign on the one and the physical, material and thing on the other hand. He argues for a novel material terminology that acknowledges the hybrid nature of code and, for example, discusses the different material properties of a code in the context of generating and using.

With our work on materiality and gestural interaction, we explore the use of different computational composites for interaction (i.e., ready-to-use universal devices such as mobile phones and self-constructed artifacts such as the multi-touch steering wheel) and analyze related material aspects (see Section 4.1).

3.1.5. Novel and Advanced Materials

The integration of novel, unconventional and advanced materials into user interfaces enables new ways of multimodal, tangible and embodied interaction. Novel and advanced materials can significantly change form factors and interactivity of user interfaces, and recent research results have exemplarily demonstrated how this development will potentially shape interactions in the future. On the one hand novel materials extend the material canon of HCI, e.g., towards textiles, liquids, substrates, or deposable materials, on the other hand especially the developments regarding new materials and processes for functional components allow the replacement of the classical rigid hardware parts. Here, one of the innovative fields is printed electronics (Steimle 2015), for instance. Printing electronics on different materials such as paper, polymer films or wood allows for a range of novel form factors such as bendable or foldable devices and large surfaces. Due to the huge potential for interaction design that derives from novel material solutions, recently an increasing number of HCI research contributions focus on novel materials for interaction and their fabrication processes (e.g., Poupyrev et al. 2016, Wang et al. 2016, Ou et al. 2016, Groeger et al. 2016). Current developments in materials science and engineering on the one and in personal fabrication on the other hand further support these activities by providing novel manufacturing processes and machines (see also Subsection 3.1.6). Especially smart materials, materials that have properties, which can be controlled by external stimuli (such as magnetic or electric fields, temperature, or moisture), are interesting for interactive applications embedded into physical materials (cf., Gandhi and Thompson 1992, Ritter 2007, Minuto and Nijholt 2013). In 1992 Gandhi and Thompson proposed the emergence of a “Smart Materials Age” and discussed three features, of which then current smart materials and structures incorporated at least one: first, *sensors*, second *actuators*, both “are either embedded within a structural material or else bonded to the surface of that material”, and third *control capabilities* “which permit the behavior of the material to respond to an external stimulus” (Gandhi and Thompson 1992, p. 42). Widespread smart materials are, for example, shape memory alloys (SMAs), piezoelectric materials, or magnetostrictive materials. Some of these have already been explored within human-computer interaction (for further application examples from architecture and design see Ritter 2007). In the remaining of this subsection, I will introduce the ideas of shape-changing interfaces and radical atoms, which both rely on material innovations, and exemplarily provide an overview of prototypes that explore the use of novel and smart materials.

Among the limitations of using classical physical objects as tangible user interfaces is that they normally are rigid and static, whereas digital data is malleable: “digital objects are easy to create, modify, replicate, and distribute” (Poupyrev et al. 2007, p. 205). To compensate these limitations, actuation and self-actuation of physical components have evolved to a major research strand. Poupyrev and colleagues define actuated interfaces as interfaces “in which physical components move in a way that can be detected by the user. There are many types of actuation, for example: change in spatial position of objects or their parts, e.g. their position, orientation; change in speed of motion of objects or their parts, e.g. speed of rotation, speed of linear motion, direction of motion; change in surface texture of objects or their parts, e.g. visible or perceived by touch; change in force applied to the user, e.g. change in force amplitude, direction, or torque.” (Poupyrev et al. 2007, p. 206). All these forms of actuation would allow more powerful forms

of tangible interaction. Recently, especially efforts regarding shape-change in user interfaces have been followed under the term *shape-changing interfaces*, which use “physical change of shape as input or output” (Rasmussen et al. 2012, p. 735). Analyzing the design space for shape-changing interfaces, Rasmussen and colleagues discussed four aspects of shape change: the types of shape change, the dynamics of change, approaches to interact with shape-changing interfaces and purposes of using shape change (Rasmussen et al. 2012). They found, for example, different functional aims ranging from using shape-change to communicate information, for dynamic affordances or to provide haptic feedback as well as hedonic aims where shape-change is applied for aesthetic, emotional or stimulative reasons.

With their vision of *radical atoms* Ishii et al. (2012) transcend these ideas for tangible and shape-changing interfaces by envisioning a new generation of materials that can dynamically change their form and appearance: “Radical Atoms is based on a hypothetical, extremely malleable, and dynamic physical material that is bidirectionally coupled with an underlying digital model (bits), so that dynamic changes of the physical form can be reflected in the digital states in real time, and vice versa.” (Ishii et al. 2012, p. 45). In this sense, radical atoms would be as malleable and flexible as pixels on a monitor screen, but contain due to their physicality many more properties and address more senses that can be used for interaction. In more detail, Ishii and his colleagues postulate three requirements for radical atoms (Ishii et al. 2012). First, they need to be able to transform according to user input or the underlying computational state. Second, they should conform to constraints, and third, radical atoms should be able to inform the user by communicating their transformational capabilities (i.e., they need to offer dynamic affordances). While this vision strongly relies on advances in disciplines such as material or chemical engineering, it is already possible to explore dedicated aspects of this general idea at larger scales. For example, the “ZeroN” prototype (Lee et al. 2011) presents an antigravity interaction element enabled by computer-controlled magnetic levitation, the “materiable” interaction technique (Nakagaki et al. 2016) allows the rendering of dynamic material properties like flexibility, elasticity and viscosity with a shape-changing interface, or “JamSheets” explores tunable stiffness of interface components by layer jamming (Ou et al. 2014).

Current shape-changing interfaces are regarded as precursors of radical atoms: while they already realize transformations triggered by users, systems or the environments, their scale is much larger than envisioned, their resolution is still low, and they generally are composed of many different materials that still need to be assembled and programmed in extensive manners. Nevertheless, recent shape-changing interfaces show in compelling ways, how powerful user interfaces of the future could be, given further material innovations support a smaller size, a higher resolution, and to higher degrees integrated interactive materials that unify rich physical and computational capabilities. The inFORM system, built by Follmer, Leithinger and colleagues (Follmer et al. 2013, Leithinger et al. 2014) explores these potentials by providing a grid of 30 by 30 pins in cuboid shapes arranged in a plane of 38 cm². Each of the pins can be separately moved up and down by actuator motors. Due to a connection via rods that transmit bi-directional force also the stiffness of a pin can be varied, which allows different haptic experiences when pins are pushed down manually. Together with depth camera sensing above the plane that tracks the user and surface objects this setting allows for a broad variety of applications. It is able to realize dynamic affordances (e.g., the system presents user interface elements that change in their shape accord-

ing to the user's actions or the system state), dynamic constraints (i.e., interaction can be guided by limiting interaction possibilities physically), object actuation (i.e., objects like marbles can be moved on the surface by the system itself by rising and lowering dedicated pins), or physical rendering of content (e.g., by physically presenting the upper surface of 3D models or bar charts). For example, with the inFORM platform it is possible to build a working prototype of the "Marble Answering Machine" (see Subsection 2.2.2) that transports marbles over the surface and collects them in dedicated holes. A further compelling application scenario is remote collaboration with physical telepresence. While current systems that support remote collaboration basically provide video and sound channels as well as the exchange of digital data, inFORM allows remote manipulation, for example. A remote person's arm movements can be physically rendered by the system, such that remote manipulations of objects are (in restricted ways) possible. Given a symmetric setup with inFORM systems at both remote locations, rendered physical objects could be manipulated concurrently.

Other works have explored the opportunities of ambient information displays in domestic and everyday environments with shape-changing interfaces. Coelho and Zigelbaum (2011), for example, explored the potentials of combining shape memory alloys with fabrics and built a number of design probes. Among these was "Sprout I/O", a grid of 6 by 6 stretchy textile strands with integrated shape memory alloys that can be bent forward and backward. Sprout I/O presents an early prototype for an interactive fabric in which angle, speed and direction of the single strands can be computationally controlled. At the same time, the fabric senses touches and provides rich visual and tactile qualities. While it presents only an exploration, potential application contexts for systems such as Sprout I/O could be interactive carpets or clothes that are used as ambient displays to present information (e.g., for indoor navigation). Similarly, the "Follow the Grass" prototype sketched out scenarios for interactive artificial shape-changing grass (Minuto et al. 2012). Recently, other approaches used the natural shape-changing abilities of 3D printed hair structures for sensing and actuation (Ou et al. 2016). In a further prototype, "Shutters", Coelho and Zigelbaum (2011) designed dynamic permeability within fabrics through creating a grid of louvers cut into a felt sheet and embedding shape memory alloy strands. Structures like these can be envisioned to be used as architectural elements controlling light and airflow or as kinetic and shadow displays in the future.

Extending the form factors and interaction opportunities of rigid multi-touch devices towards bendable devices that allow for richer manipulations and more diverse haptic feedback has evolved to an important research topic within human-computer interaction. Recently, several approaches for bendable mobile devices (e.g. Lahey et al. 2011, Strohmeier et al. 2016) as well as more general interaction concepts for flexible devices (e.g. Steimle et al. 2013, Khalilbeigi et al. 2012) have been presented. Additionally, rich sensing capabilities that go beyond simple touch sensing allow novel, more fine-grained interaction techniques. Based on their previous work on a flexible piezoelectric sensor that combines touch, pressure and bend sensing (Rendl et al. 2012, 2014) Rendl and colleagues built FlexCase, an interactive smartphone cover with input and output facilities and the capability to communicate with the smartphone (Rendl et al. 2016). It allows bend and touch input and also contains an e-paper display that can be used as secondary display together with the LCD of the mobile phone. Due to this combination of materials a range of novel interaction techniques and application scenarios is possible. For instance, having the flip cover opened

with the sensor and e-paper display on the left and the mobile phone on the right the device could be used like a book with two pages and page flipping mechanisms by bending a corner of the left page forward or backward. Other scenarios the authors describe include bend sensing for map interaction or zooming pictures, bi-manual interaction for content transfer between pages, using continuous bend input for gaming or back-of-device interaction for navigating content.

Be they traditional, smart, passive, high-tech, inexpensive, low-tech, unconventional or organic – the interaction materials of the future will be manifold and the potential material diversity for human-computer interaction is tremendous. I have highlighted some examples that use “classical high-tech” smart materials, but there are many more approaches to explore. Recent research like “Cillia” has demonstrated for example that materials can get smart features that are useful for input and output just by exploring innovative shapes and fabricating these in a smart way. Smart materials can also contain natural ingredients. “BioLogic” (Yao et al. 2015), for example, presents a shape-changing material that contains bacteria which expand when exposed to moisture. Franzke (2013) built an electroluminescent loudspeaker using natural materials.

Despite all these explorations within HCI, the field of “novel and advanced materials” is still young. Dedicated methods to work with smart materials in HCI, for example, have basically not been addressed yet. Among early approaches here is the recent work by Barati et al. (2016), in which they presented functional demonstrators to support the understanding of smart materials by design students.

This research contributes to this theme by covering novel materials as part of ephemeral UIs and by discussing them as a starting point for smart and advanced materials that pick up certain ephemeral properties (see Section 4.3). For example, the work discusses the value of advanced materials that change over time, get “patina”, or have limited lifespans. On a conceptual level, the *interaction material profile* (see Subsection 3.2.2) offers a number of material dimensions that support understanding the complex aspects of novel and advanced materials.

3.1.6. Making, Craft, and Do-It-Yourself

Making has always played an important role in interaction design, especially in design disciplines (Löwgren 2016). Nevertheless, a focus on making, craft, and do-it-yourself (DIY) cultures in HCI has recently grown into a major research strand that is closely linked to the increasing intertwining of physical and digital materials. On the one hand, the values and qualities of traditional craft and craft materials get re-discovered. Especially within computer-based approaches in the past these were disappearing to a large extent. On the other hand, novel fabrication processes such as 3D-printing, lasercutting or CNC-milling bring together computation, high-tech machines and a broad variety of physical materials, reach with the concept of “personal fabrication” (Gershenfeld 2005, Mota 2011) a large non-expert user group, and have the potential to fundamentally change aspects of making and customization in our society. From these developments a number of questions and topics derive for HCI that have been started to be addressed. E.g., how can we integrate values of craft into interaction design? How can we design tools and systems that allow

to use them in a craftsmen manner? How can we better integrate technology and classical craft approaches? How can HCI as a discipline design for the growing community of makers? How can the tools and results from the DIY community be used to design novel interaction materials and interfaces? In the following, I focus on two (not mutually exclusive) areas: *hybrid crafting* and *do-it-yourself and maker communities*. Both areas influence applied materials and material processes in HCI.

With *hybrid crafting* Golsteijn et al. (2014) understand “everyday creative practices of using combinations of physical and digital materials, techniques or tools, to make interactive physical-digital creations”. They discuss four areas of related work: “craft in design and HCI”, “Informing design through the study of craft practice”, “combining technology with traditional means of crafting”, and “tangible interaction and crafting platforms”. In their own work, the authors explored hybrid crafting with personal media and their toolkit “Materialise”. Based on this, they formulated a number of guidelines regarding the craft context, the craft process and its results, e.g., “envision a concrete use context”, “integrate physical and digital making phases” or “enable creations that can be ‘made to last’” (Golsteijn et al. 2014, p. 609). Bardzell et al. (2012) investigated qualities and values of craft and discussed derived aspects for quality in design disciplines. Rosner and colleagues furthermore conducted a number of studies about the meaning and quality of craft materials, processes, collaborations and artifacts in different domains such as bookbinding (Rosner et al. 2011, Rosner 2012) or knitting (Rosner and Ryokai 2009, Goodman and Rosner 2011). They also explored applications that offer novel values around the crafters’ practices such as “Spyn”, a mobile application for knitters (Rosner and Ryokai 2010). In other works, Rosner and colleagues introduced the notion of “material traces” to HCI (Rosner et al. 2013) or investigated values in repair (Rosner and Ames 2014, Houston et al. 2016). Murer and colleagues discussed an “un-crafting” approach to HCI, analyzing tangible practices for deconstruction (Murer et al. 2015). Zoran and colleagues presented novel approaches for computer-based craft tools that still allow a craft-based interaction and offer craft experiences. Among these were “FreeD” (Zoran and Paradiso 2013), a freehand sculpting tool, and “the hybrid bricolage” (Efrat et al. 2016), a system that supports parametric design for sewing, for example.

With the goal to better integrate technology and classical craft approaches Leah Buechley and her team in the high-low tech group at MIT Media Lab have presented prototypes and “untoolkits” (Mellis et al. 2013b, see also Subsection 3.1.4) or “kits-of-no-parts” (Perner-Wilson et al. 2011) that focus on using electronics together with and similar to traditional craft materials (Buechley and Perner-Wilson 2012). They explored craft techniques such as sewing and knitting or drawing and painting and combined them with electronics, e.g., in the form of handcrafted textile interfaces (Perner-Wilson et al. 2011) or sketched circuits and paper-based electronic pop-up books (Qi and Buechley 2010, 2014). While among the authors’ goals is to explore educational aspects of their practices e.g., by “leveraging visibility” of electronic components (Buechley 2010) – as opposed to the vision of invisible interfaces as part of ubiquitous computing – they also applied their approach to demonstrate, how everyday domestic environments can become interactive in an unobtrusive way by integrating novel materials. For instance, Buechley and colleagues presented “Living Wall”, a wallpaper with ambient input and output facilities that can be used for applications such as interactive lighting, environmental sensing, appliance control, or as ambient information display (Buechley et al. 2010). The Living Wall approach is characterized by a visu-

ally appealing integration of high and low tech materials. This integration is not based on hiding technical and functional components but on inventing novel functional components from diverse materials and with new form factors. Living Wall contains a layer in which the whole circuitry needed to connect sensors, actuators and communication elements is painted with a conductive paint, which at the same time is part of the decorative pattern of the wall. Beneath, the wallpaper consists of a layer of magnetic paint, so that electronic modules can be freely and flexibly attached by magnets to dedicated areas on the wall. Among these components were, for example, a microcontroller, LEDs, motors, shape-changing paper flowers, and several sensors measuring light temperature and motion. With this setup, a broad range of domestic applications are possible without the need for classical computer-based devices.

Next to works like these that combine aspects of craft and human-computer interaction, recent developments in *personal fabrication, do-it-yourself and maker communities* have influenced HCI research (Döring 2014, Lindtner et al. 2014, Roedl et al. 2015). While digital fabrication has been used in industry for decades already (Mueller and Peek 2016), only young inventions, such as comparably low priced and open source 3D-printers, gave rise to the idea of “personal fabrication” (Gershenfeld 2005), a “democratization of manufacturing” (Mota 2011) that offers everyone access to extensive and high-tech fabrication processes. Many of the tools developed and used by a growing open-source and maker movement are very valuable for the prototyping and developments of novel user interfaces within HCI research itself. Williams et al. (2012) for example, argue that much of the work conducted in the area of tangible interaction would not be possible or would be so much more complicated and expensive without all the efforts conducted within the maker movement, e.g., the development of the relatively cheap and easy-to-use open source microcontroller Arduino (Kushner 2011), which became one of the major prototyping platforms for the HCI research community. But beyond this aspect, all these novel fabrication machines and processes with the everyday non-expert user as target group, also including kids or older people, demand for novel user interface concepts as well as hard- and software solutions (Mueller and Peek 2016). HCI researchers like Müller and colleagues or Weichel and colleagues have addressed this research direction and developed novel machines and interfaces for personal fabrication, such as LaserOrigami (Mueller et al. 2013), faBrickation (Mueller et al. 2014), constructable (Mueller et al. 2012), MixFab (Weichel et al. 2014) or ReForm (Weichel et al. 2015).

A further strand of research addresses how HCI as a discipline can design for needs, values and context of the growing community of makers. Kuznetsov and Paulos (2010), for example, conducted a survey on the expert amateurs in DIY communities and their appropriation of human-computer interaction technologies. They found that DIY communities lower the barrier to enter a domain, that learning by “a give and take dialog” (Kuznetsov and Paulos 2010, p. 7) is central, that the need to express individual creativity plays a big role and that open sharing is a core motivation and value. As design implications for HCI they suggest to support the integration of physical and digital domains, new forms of knowledge transfer and iterative studio cultures by novel tools and platforms. In their following research, Kuznetsov and colleagues have analyzed the practices of a variety of specific DIY cultures from an HCI perspective, such as BioHacking (Kuznetsov et al. 2012) and Food Science (Kuznetsov et al. 2016). Wang and Kaye (2011) identified eight common themes in hacker practices as example for inventive leisure practices, among which where *hacking as identity, skill, reputation and participation*. Tanenbaum et al. (2013) see a

democratized technological practice and find especially pleasure, utility and expressiveness as important values for technology in the maker movement. The authors suggest supporting the maker movements' needs and values from an HCI perspective by designing for these values and providing infrastructures and platforms that enable creativity. Overall, the interest of the HCI community in topics around maker communities and personal fabrication can also be seen in the increasing number of related workshops organized at academic HCI conferences.¹ This work contributes to the growing body of research around DIY and HCI by providing and evaluating an end user toolkit, which was configured to design an alarm clock with preferred functionality without the need to program (see Subsection 4.2.1). In the selection of materials for this toolkit, we combined classical craft approaches (e.g., paper, foam board, scissors, stickers, glue) with state-of-the-art personal fabrication technologies (e.g., 3D printing). Moreover, we discussed future directions of personal fabrication and end user customization in (Schmidt et al. 2011) as well as connections between DIY and HCI in (Döring 2014).

3.1.7. Sustainable Interaction Design

Taking a materials perspective on human-computer interaction also brings issues of sustainability into the focus. Where do the materials used come from? How long do they last? Can they be recycled or reused? Do people value them for a long time? Aspects like these have been largely ignored by human-computer interaction and computer science and only started to get addressed in the last decade. Sustainable development in general got more recognized in recent years (Adams 2006), whereas agendas on sustainability often address three pillars: economic, social and environmental sustainability (Adams 2006, p. 2). Based on these three areas, Knowles and colleagues identified 10 key questions regarding sustainability in computing addressing *e-waste*, *CO₂*, *monitoring*, *behavior*, *renewables*, *resources*, *efficient technology*, *efficient society*, *sustainable society* and *consumption* (Knowles et al. 2013). DiSalvo and colleagues further investigated the emerging field of sustainable HCI and found five established genres in the area: *persuasive technology*, *ambient awareness*, *sustainable interaction design*, *formative user studies*, and *pervasive and participatory sensing*. Within these, especially the field of sustainable interaction design focuses on material effects. Eli Blevis discussed sustainability as central focus of interaction design and proposes “a rubric for understanding the material effects of particular interaction design cases in terms of forms of use, reuse and disposal” (Blevis 2007, p. 503). He argues that design choices should account for environmental effects and sustainable behaviors. His ten aspects of the rubric are: *disposal* (e.g., do physical materials get disposed?), *salvage* (e.g., does the design include previously discarded physical materials), *recycling* (e.g., does it make use of recycled materials?), *remanufacturing for reuse* (e.g., is the renewal of physical material for reuse possible?), *reuse as is* (e.g., can the design be directly reused by someone else?), *achieving longevity of use* (e.g., does it allow for long-term use?), *sharing for maximal use* (e.g., can it be used by many people?), *achieving heirloom status* (e.g., does the design motivate preservation?), *finding wholesome alternatives to use* (e.g., does the design not need additional physical resources?), and *active*

¹E.g., “FAB at CHI” 2013 (Mellis et al. 2013a), “PerFab 2013” (Lau et al. 2013), “Fabrication & HCI” at CHI 2016 (Fuchsberger et al. 2016), “CrossFAB” at CHI 2016 (Mueller et al. 2016), and “Digital Craftsmanship at DIS 2016 (Jacobs et al. 2016)”.

repair of misuse (e.g., does it repair harmful effects of unsustainable use?). Blevis suggests to use these aspects to guide the analysis of current practices as well as to design for a more sustainable future and also proposes a number of open research questions that demonstrate that the field of sustainable interaction design is broad, important and at the time of the publication little explored.

While publications such as the above mentioned focus on a fundamental overview and topics of the emerging field, other works have exemplarily investigated specific aspects related to sustainability and HCI. Among these are, for instance, Hanks' and colleagues study on undergrad students' attitudes towards sustainability (Hanks et al. 2008) or, more recently, Roedl and colleagues' analysis of the difficulty to establish a practice of sustainable interaction design within the maker movement, given the fact that designed obsolescence of digital artifacts is widespread (Roedl et al. 2015). Other research projects have explored users' relations to digital and physical possessions (Odom et al. 2009), values in repair (Rosner and Ames 2014, Houston et al. 2016) and of material traces (Rosner et al. 2013). Besides research on sustainability and computing Fair-IT initiatives for example have addressed the issues of current IT production and advocate socially acceptable productions (Wölbert 2013).

With our work we provide novel approaches for addressing sustainability and HCI by showing and analyzing opportunities to include natural materials as part of ephemeral user interfaces (see Section 4.3). Furthermore, our end-user toolkit realizes a novel and original modular composition of hard- and software elements (see Subsection 4.2.1). This allows for simple exchanging, repairing or reusing parts and thus is designed for personal appropriation and longer life span. Moreover, also simple materials like cardboard or paper and other biodegradable materials can be used as part of a device.

3.1.8. Understanding the Roles of Materials in Practices

The theme *understanding the roles of materials in practices* as it is framed here, encompasses analytic perspectives on materiality in HCI, largely applying methods and theories from social science, anthropology and material culture. In future, this currently growing field will likely be further subdivided. For the purpose of this overview, I focus on major recent research strands focusing on analytic approaches. The works span from theory and philosophical approaches to ethnographic analysis of practices and considers the whole spectrum from digital to physical materialities. Here I address two areas, first, *theoretical contributions*, second, *ethnographic work on material practices to understand aspects like the agency, value, meaning or power of materials in specific contexts*.

Among *theoretical contributions* in this area are Blanchette's as well as Dourish's and Mazmanian's analyses of material aspects of information technology (Blanchette 2011, Dourish and Mazmanian 2011), both grounded in the tradition of material culture (cf. Miller 2005), and Fuchsberger and colleagues' framing of the role of materiality in interaction design based on Latour's Actor-Network Theory (Latour 2007) and McLuhan's media theory (McLuhan 1964).

Blanchette addressed the digital as material and wrote a “material history of bits” (Blanchette 2011). He argues that “information cannot exist outside of given instantiations in material forms” (Blanchette 2011, p. 1042). This means that constraints of materiality apply to bits and information as well. Blanchette criticizes that the perspective of seeing bits as something immaterial is misleading and problematic, as how related material aspects take effect through information technology cannot be fully understood. To address this, he suggests to take a historical perspective and demonstrates this by analyzing material constraints of the von Neumann machine and their effects, for example. Overall, he shows that information technology is not independent from the material world. Similarly, Dourish and Mazmanian (2011) addressed media as material, focusing on “material properties of these forms [i.e. the material form of digital stuff] and their consequences for how people encounter, use, and transform them” (Dourish and Mazmanian 2011, p. 4). They presented “five conceptualization of the materiality of information in the context of digital technology” (Dourish and Mazmanian 2011, p. 5). Among these were *the material culture of digital goods*, *the transformative materiality of digital networks*, *the material conditions of information technology production*, *the consequential materiality of information metaphors*, and *the materiality of information representation*. The last aspect was discussed in more depth, e.g., by taking the example of photography where material constraints have massively changed with the transfer to digital photography and influences our practices and values.

To provide a theoretical framing of the role of materiality in interaction design, Fuchsberger et al. (2013) related ongoing materiality discourses in HCI to McLuhan’s work on media theory (McLuhan 1964) and Latour’s Actor-Network Theory (Latour 2007). In both works, McLuhan’s and Latour’s, materials are regarded as having an active role in the relationship to humans (as extensions of man and actors in a network). For Fuchsberger et al. materials in interaction design can depict content as well as representations within interactive artifacts. Both can consist of physical or digital materials. Media, which is needed to represent information, is regarded as material: “Thus, media can be any material that allows to interact with the information” (Fuchsberger et al. 2013, p. 2854). By doing so, the authors tie the materiality discourse up to McLuhan’s media theory that sees the media, i.e. the used materials, as more important for “messages” than the content itself (McLuhan 1964). He argued that the four stages of cultural history (a primitive tribal era, an audile era, the gutenbergs galaxy, and the electronic age) affected and involved the human senses differently. The current electronic age has the potential “to affect and transform all human senses” (Fuchsberger et al. 2013, p. 2855), but this requires the humans – designers as well as users of interactive artifacts – to overcome the sensual patterns from the past era. Interaction designers need to find novel ways of interactions, explicitly considering and overcoming former ways to interact, and be aware that sensory effects a user of this artifact later on might have can be different from their own ones during the design process. As the designer and the user are only connected through the interactive artifact, it is worthwhile to further understand and model the role of the artifact, i.e., the materials involved. For this, Fuchsberger et al. suggest to apply Latour’s Actor-Network Theory (Latour 2007) that considers humans and non-human entities, i.e., artifacts, materials, technology, as actors in a network. Latour’s theory is interesting for interaction design, as interactive artifacts, designers and users can be modeled as actors in a network. Moreover, as the connection between designers and users only is mediated through the interactive artifact, its role as an actor in the designer-user-relation becomes crucial. Overall, the authors suggest the Actor-Network Theory as a framing for how to describe design in design

research, which heavily relies on documentation, but yet has no established processes how to do this. In a follow-up work, Fuchsberger and colleagues explored this approach and suggested a notation to describe the “In-Between of Interactive Artifacts and Users” (Fuchsberger et al. 2014a, p. 451).

Further research focuses on *ethnographic work on material practices to understand aspects like the agency, value, meaning or power of materials in specific contexts*. Jacucci and Wagner (2007) for example investigated the roles of materiality for collective creativity and found a number of aspects, how materials unfold in creative group works. Observing architecture students working in mixed reality environments, they found that material diversity and multi-modal richness guided and extended the communication process. Thus, materials shaped the overall action “in their peripheral, evocative, and referential function” (Jacucci and Wagner 2007, 75). Additionally, their observations showed the importance of spatiality, in form of the physical objects’ shapes and locations as well as related to bodily engagement. But not only the spatial properties of materials matter, also how the materials are transformed over time contributes to collective creativity. Tholander et al. (2012) investigated how interaction materials “talk back” (referring to Schön 1984) to designers during the design process. They focused on the agency of these materials., i.e., their active role in the design (which implies an emerging relationship between the material and designer(s) as well as other materials), and found a strong influence on shaping resulting ideas. Tholander and colleagues emphasize that the concept of agency differs from affordance, as “affordances [...] can be discovered by users, while agency emerges in a continuous on-going dialogue between humans and things in a specific context” (Tholander et al. 2012, p. 2501).

An important application area to study the meaning of objects and the implications for a meaningful interaction design is the home context. Petrelli and Light, for example, conducted a study on christmas-related family rituals. Starting from the three different ritual phases they identified, the authors present inspirations for augmenting the rituals by new technology in meaningful ways (Petrelli and Light 2014). In order to better understand the value of personal inventories and to be able to apply insights to the design of interactive artifacts, Odom and colleagues carried out a number of ethnographic studies in the context of households. They conducted interviews to understand, for example, why people liked their kitchen utensils, flashlights or wooden chairs so much and derived a number of implications for design (Odom et al. 2009) to construct—physical or interactive—artifacts that are valued. These implications relate to the object’s function (single purpose is more likely to continue to last and to be valued over a longer period of time), its symbolism (which, especially when arising from personal histories, can generate a high strength of attachment), and the material qualities (i.e. physical materials like wood inspire durability while others do not) (Odom et al. 2009). Furthermore, the authors recommend to design opportunities for deeper engagement with the products, for letting the device evolve traces of use and patina over time, for giving users opportunities to augment and customize the object, and, to enhance the perceived durability by choosing high quality physical materials while allowing to keep digital and computational components up to date over time. In other studies Odom and colleagues (e.g., Odom et al. 2010) also investigated the value of so called “virtual possessions”, i.e. digital picture, music or email collections, among young users and found a number of needs around personal digital collections that could be supported better by future systems, e.g., the demand for expressive storage and immediate accessibility as well as for using different sets of mate-

rials for self-presentation to varying receivers. Overall, a some further studies started to shed light on the value of physical and digital possessions (Petrelli and Whittaker 2010, Gruning and Lindley 2016, Odom et al. 2011, Gruning 2016, Odom et al. 2014, Gerritsen et al. 2016). Moreover, Glöss (2012) proposed a structural approach to integrate the cultural value of objects into design of digital materiality.

Understanding material practices in specific domains or regarding certain conceptual foundations and applying the results to human-computer interaction has been the focus in a number of exemplary research works. (Rosner 2012), for example, examined the practices of collaboration in a bookbinding workshop and highlighted the importance of the involved materials – physical materials such as paper, leather or glue, tools or computer and mobile phone – for the collaborations. Moreover, they identified different configurations of collaborations: *material-material collaborations*, *material-human collaborations* and *material-workspace collaborations*. To better grasp how digital, hybrid and physical materials affect practices, they suggest to understand materials, first, as compositional elements, second, as surfaces, and, third, as spatial-temporal flow. In a different work Fernaeus et al. (2012) took a historical perspective and analyzed material and interaction qualities of the jacquard loom in order to rethink current concepts for computational devices. Among their results were four themes: *materiality and digital representations*, *graspability and complex mechanics*, *whole body interaction* as well as *sustainability and age*. Regarding *materiality*, the authors highlight that, similar to other works presented earlier, “the different materializations that digital representations take unavoidably affect how they play out in meaning making practices.” (Fernaeus et al. 2012, p. 1598). Their *graspability* theme reveals that tangibility does not necessary mean that something needs to be simple and immediately understandable. Third, *full body interaction* with the jacquard loom involved a wide range of aspects that go beyond typical current systems, e.g., human weight, size or muscle strength is addressed in the design. The last aspect, *sustainability and age*, is related to other research works presented above about why and how things are valued as well as the current lack in HCI to address related aspects, e.g., by putting emphasis on a high quality of physical materials and how artifacts age (getting material traces or patina, etc.). Another study that focuses on material practices in a specific domains, is Tanenbaum and colleagues work on Steampunk practices (Tanenbaum et al. 2012). In their results, the authors suggest a number of implications, such as the potential of design fictions to direct the focus towards social meanings and values of objects as well as the advantages of their DIY and appropriation techniques for HCI. Other interesting research has been recently conducted by Tsaknaki and Fernaeus (2016), who focused on the Japanese philosophical concept of ‘Wabi-Sabi’ and applied it to support reflection in interaction design. Wabi-Sabi, in short, means that “nothing lasts, nothing is finished and nothing is perfect” (Powell 2004). While promotions of current technology present these as the opposite – lasting, and being finished and perfect –, fast obsolescence is the reality in many hard- and software domains. Designing with a focus on Wabi-Sabi-inspired principles targets towards more authentic interactive devices and novel perspectives on their long-term impact. Last but not least, this approach puts material aspects of interactive artifacts and computing into the focus.

Understanding the roles of materials in practices has been a focus in several of the research projects as part of this work. For example, in the study on tool use in a collaborative tabletop game we analyzed the material agency of a physical and a digital tool and found differences in

individual ownership and announcement of tool use (see Subsection 4.2.2). The design workshop with the end-user toolkit revealed insights about how the involved materials influenced the design process. It also revealed that these materials need to be carefully selected in order to fit the potential users as well the intended device best. As part of our research on using soap bubbles for interaction, we conducted an in-the-wild (Döring et al. 2012b) as well as an in lab study (Döring et al. 2015) that both focused on understanding how soap bubbles are perceived, approached and used as part of a user interface as well as how they encourage certain behaviors (see Subsection 4.3.2).

3.1.9. Discussion

This section shows how manifold and diverse the themes are that together contribute to a materials perspective on human-computer interaction. With the increasing interweaving of computation and physical objects all these themes will become more important in order to fully understand how interactive artifacts unfold and affect their users as well as how they need to be designed. In the following, I will briefly discuss theme-related important future research directions that evolve from this survey. The first two themes cover *material-centered theory* and show that first concepts as well as frameworks and methods for materials in HCI have been addressed. Nevertheless, understandings of what a material is and what kinds of materials should be distinguished largely vary and more work is needed in order to reach a better agreement and to dissect and name relevant factors. The overview on frameworks and methods as part of theme 2 reveal that yet little work has been conducted on encompassing methods for designing with a material focus. Analyzing *the material-centered practice* in HCI, I structured this field into: *physical materials for interaction*, *the computer as material* and *novel and advanced materials*. The survey showed that research has started to systematically investigate selected physical material aspects for interaction and that these studies are insightful. To date, our knowledge on physical material aspects for interaction overall is still limited. Thus, more studies and a more systematical integration of their results are needed in order to better and more comprehensively guide design decisions in the future. The computer as material addresses a novel class of material properties that are linked to behavior over time. This survey revealed that first concepts and methods address these but, overall, also shows that further tools and methods are needed to communicate these properties to interaction designers and users. Similarly, in the growing area of novel and advanced materials for interaction merely any tools, methods or techniques have been developed to support the inter- and transdisciplinary work that is necessary to advance this field, e.g., in order to bring materials scientists and HCI researchers together early in the design process or to facilitate the understanding of smart materials for interaction designers. This is especially relevant, as in the future, designing a novel material for a user interface could become as common as picking an existing one. The two *material-centered fields* I covered, DIY and sustainability, both mark omnipresent themes that are regarded as important in the society as a whole. For HCI, the DIY movement and rise of personal fabrication brings new application areas and use cases into the focus, e.g., the need to design for makers instead of traditional users (see also Roedl et al. 2015), which demands for novel tools, processes and materials. Sustainability in general is a central and important concern nowadays. Nevertheless, in computing and HCI, sustainability aspects are still only very limitedly covered.

While a rethinking and orientation towards more sustainable solutions in industry and politics is clearly needed, there is a strong demand for research on sustainable interaction design. Blevis' introduction to 10 relevant aspects for a sustainable interaction design from 2007 still provides excellent guidelines for research directions that have not yet been sufficiently covered (Blevis 2007). The last theme, *understanding the roles of materials in practices*, puts the focus on analyzing material aspects. This survey showed that especially ethnographic work on understanding the agency, value, meaning and power of materials provides very valuable insights that are relevant for designing user interfaces and interactive artifacts. Thus, interdisciplinary research in this area should be encouraged and mechanisms are needed that feed the derived insights back into design processes.

Overall, while the eight material themes provided in this subsection do not necessarily cover all possible material aspects and will further develop and change over time, this survey gives a comprehensive overview of this novel and growing field that is still challenging to grasp and structure in its full diversity.

3.2. A Framework to Understand and Inspire How Material Aspects Shape Interaction

In this section, I introduce the material framework used in my work to discuss material aspects of user interfaces. It consists of three parts. The first one addresses *material terminology for HCI*: types of materials and materiality. The second part presents a structure for an *interaction material profile* and introduces micro and macro perspectives to material aspects as novel dimensions. Finally, the third part, the *physicality representation spectrum*, addresses how real world objects get materialized and represented in user interfaces on a digital-physical scale. The materials framework presented in this section builds the underlying structure for the discussion of how material aspects shape the interaction in the conducted case studies in Chapter 4.

3.2.1. Material Terminology: Materiality and Types of Materials

Building on previous use of material-related terminology in HCI as presented in Subsection 3.1.1, I will explain in the following how the terminology is applied in the scope of this work.

Materiality: The term *materiality* refers to the discourse about material aspects in general. Addressing materiality in HCI encompasses a constructive as well as an analytic lens. Furthermore, materiality includes addressing the matter of things as well as understanding how materials unfold, act and how humans appropriate them. It can embrace knowledge and methods from diverse disciplines such as materials science and engineering, arts, design and architecture, material culture or sociology.

Material: What is understood by the term *material* largely differs, often depending on the context and dedicated point of view (Wagner 2001). Vallgård and Redström already stated that “the general concept of material is an ill-defined one even within material science” (Vallgård and Redström 2007, p. 514). They also argue that the level of abstraction matters, e.g., there is no clear distinction between structure and material, as materials, for example, can be considered structures on a molecular level. Within art history, substrates such as water, fog or even fire, which is, strictly speaking, a chemical reaction to a material, but also artifacts that consist of different materials themselves can be regarded as materials for art.² It always depends on the point of view. For the purpose of a material terminology for human-computer interaction, we need to highlight the importance of the level of abstraction and generally include all possible levels, from raw materials to compound artifacts. Moreover, also digital materials need to be included. Thus, I distinguish between *physical materials*, *digital materials*, *computational materials* and *computational composites*.

Physical Materials: *Physical materials* encompass *tangible* physical materials (such as raw materials, substrates and artifacts with solid or liquid state of matter) as well as *intangible* physical materials (such as materials with gas state of matter).³ Following the above mentioned approach, all possible levels of abstraction are included, from raw substrates to complex artifacts. Moreover, materials can contain inorganic or organic compounds as well as natural or artificial matter. Example physical materials we covered in our case studies were, e.g., water, soap bubbles, fog, plastic, wood, and classical craft materials such as foam board, paper, stickers and cutter. See Subsection 3.1.3 for further example physical materials for interaction.

Digital Materials: *Digital* or *virtual materials* refer to algorithms, software, or code (Ozenc et al. 2010, Lindell 2014) and data or information as material (Dourish and Mazmanian 2011, Fuchsberger et al. 2014a). Although both can neither be stored nor experienced without additional physical materials, it is important to be aware of the properties of digital materials in order to understand how these affect the design process or the outcome when the digital materials are applied within artifacts, for example. See paragraph on software as material in Subsection 3.1.4 for further details.

Computational Materials: *Computational materials* are hardware components like sensors and actuators. Inarguably, these contain physical materials. Nevertheless, similar to Kwon’s and colleagues’ assessment that “the physical characteristics only protect the computing process” (Kwon et al. 2014, p. 654), I argue that the focus is on understanding their properties as interaction design material, i.e., properties that are dynamic and change over time or in relation to the environment for example. Like digital materials, computational materials also need additional physical materials to be able to be fully experienced. See paragraph on hardware as material in Subsection 3.1.4 for further examples of computational materials for interaction.

Computational Composites: The term *computational composites* was introduced by Vallgård and Redström (2007) and has already been introduced in detail in Subsection 3.1.4 above. In gen-

²For further explanations and examples see (Wagner 2001), (Wagner 2002), and (Wagner et al. 2010).

³Using immaterial materials for interaction has been discussed by (Kwon et al. 2014) for example.

eral, computational composites present compositions made of computational, digital and physical materials. Thus, the term denominates artifacts that contain hardware and software as well as physical materials such as casings or other surface materials for example and highlights that, through this composition, a new composite material has been designed, with novel properties that exceed the sum of its parts. Other terms that are used for compositions of hardware, software and physical materials, although with a less strong focus on the materials structure, are *digital artifact*, *hybrid artifact* or, if it involves interaction, *interactive artifact*.

This distinction of material terms is, similar to other uses in the literature, pragmatic in the sense that the selection of term to some degree depends on the chosen point of view rather than on a very formal distinction. Overall, it brings together emerging perspectives in human-computer interaction and at the same time provides a useful terminology to discuss and understand how aspects of different materials involved take effect. In practice, these get increasingly interweaved, so that some researchers explicitly do not address physical and digital aspects separately (e.g., Giaccardi and Karana 2015) and terms such as material *texture* (Robles and Wiberg 2010) reflect this. Furthermore it is important to look at materials and their properties not as “properties per se” but as embedded into contexts and practices (e.g., Giaccardi and Karana 2015), this will be addressed in the *Interaction Material Profile* in the next subsection. In the scope of this research, I am specifically interested in exploring and understanding aspects of physical materials for interaction. Thus, the following two framework contributions put a focus on physical materials as part of interactive artifacts.

3.2.2. The Interaction Material Profile: Material Aspects on a Micro and a Macro Level

We still lack a structure for an interaction material profile that encompasses quantifiable properties of a material as well as interpreted and experienced material aspects as they occur when embedded into human practices. The interaction material profile aims to provide this and is inspired by two approaches to describe material profiles in other disciplines: first, the “five dimensions of materials information” compiled by Ashby and Johnson (2010) for product design – which are: *the engineering dimension, usability, the environment, aesthetics, and personality* – and, second, a material-iconographic lexicon of artistic materials by Wagner et al. (2010). While the first work aims to support using materials in product design, the second work focuses on providing structured examples of material uses in art to support the understanding and reflection of these. Both, designing with materials and analyzing their aspects in use is important for HCI. In the lexicon of artistic materials, the authors addressed typical uses and specific example applications of unconventional and traditional artistic materials and especially focused on material meanings that contribute to the meanings of the artists’ works in the selected examples. Each material entry applies a structure to describe a material profile consisting of: a description of the material use in an example artwork with figure, general material characteristics, a history of the material’s artistic uses, as well as a history of the material’s meanings in art and cultural contexts. Based on this background, the use of the material in the initial example is qualified. Each article ends with a collection of relevant quotes and literature references. Starting from this structure with a

focus on qualitative aspects and Ashby's and Johnson's approach that integrates quantitative and qualitative material aspects, I designed the interaction material profile.

In the interaction material profile, I distinguish between two levels of analysis: *material aspects on a micro level* and *material aspects on a macro level*. Micro level aspects refer to aspects of the material itself (e.g., its technical properties and structure, its form factors) and to aspects of the interaction with the material on a technical, fine-grained level (e.g., in what way it addresses the human senses and interaction modalities, how it can be touched). Macro level aspects take a more holistic perspective and consider contexts, semantics and experiential qualities, for example a material's meanings in specified cultural contexts, the purpose a material is applied for, or the emotions that are (potentially) evoked when interacting with the material. Furthermore, the profile distinguishes between material aspects that a material generally comes with (*general aspects*) and those that can only be discussed in the context of a specific application it is used in (*application-specific aspects*). While materials come along with some inherent material properties, the overall experience of an interaction material cannot be regarded without the specific user interface it is embedded in. This means, for a given material, an interaction material profile ideally consists of general material aspects on a micro and macro level as well as of a set of example applications where the material is used. For each example application, micro and macro level material aspects are described as illustrated in Figure 3.2. In the following, I will explain the interaction material profile's components. The interaction material profile is also covered in (Döring 2016a).

General Material Aspects on a Micro Level

First, as part of the general material aspects on a micro level, the material gets characterized by its most important *technical attributes*, which can include physical, mechanical, electrical, thermal etc. attributes (see Ashby and Johnson (2010) for examples of technical material profiles). A second aspect is dedicated to the material specific *form factors* that can be generally relevant for its use in user interfaces (e.g., material specific shape, constraints, and affordances). In case of computational composites and digital materials, properties as well as form also would encompass temporal aspects.

General Material Aspects on a Macro Level

The macro level on the general material aspects gives an overview over the *meanings* a material has in different contexts, which could be historical contexts, cultural contexts, or application contexts, depending on the material. This information is especially relevant for everyday and traditional materials. When used for inspiration, it can potentially support the inclusion of more meaningful material aspects into interaction, be it by including a physical material directly, or by applying its properties and meanings metaphorically to other physical and digital representations. A second, related aspect refers to *typical application contexts* for the material, if applicable, to

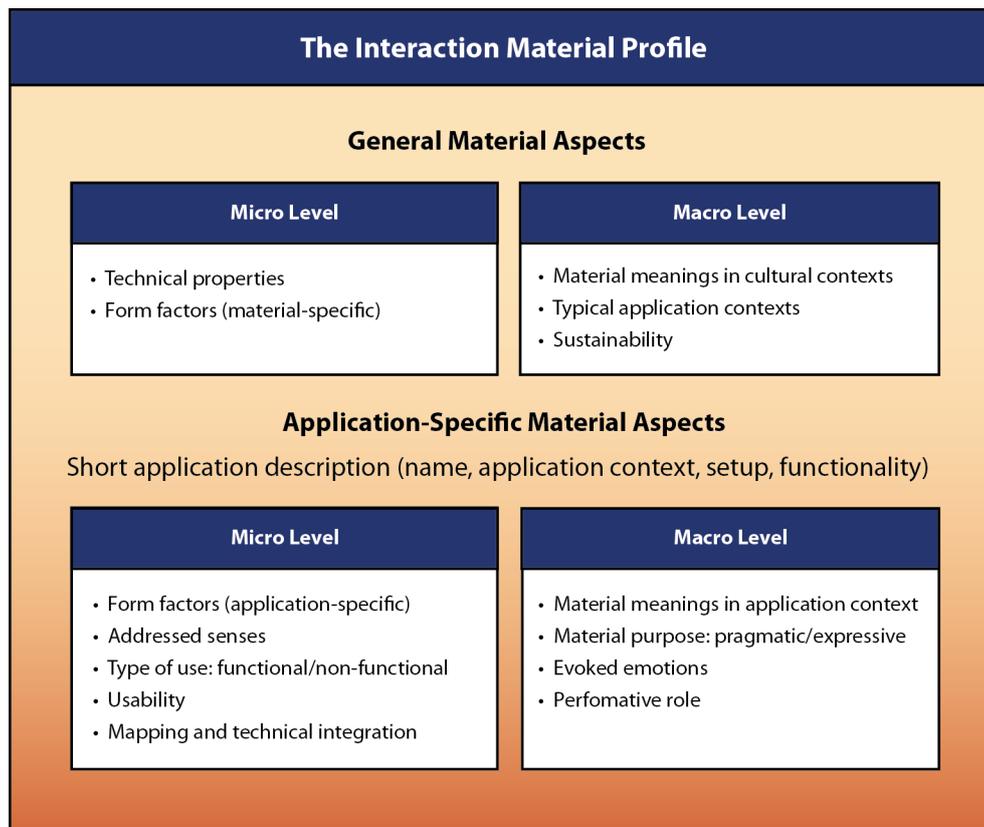


Figure 3.2.: The Interaction Material Profile. A full interaction material profile includes general material aspects as well as a set of exemplary applications, in which the material has been used with an application-specific material profile on a micro and macro level for each application.

give an overview over previous uses of the material for human-computer interaction. A third aspect is dedicated to the *sustainability* of the material, an increasingly important aspect that, amongst others, refers to lifetime, disposal, or reuse (Blevis 2007).

Application-Specific Material Aspects on a Micro Level

After a brief explanation of the *example application and user interface* (e.g., name, application context, setup, functionality), the profile addresses application-specific material aspects on a micro level. Among these are *application-specific material form factors*, *addressed senses*, the *type of use* of the material in the user interface (functional vs. non-functional), *aspects of usability*, as well as aspects of *mapping and technical realization*. *Application-specific material form factors* relate to shape, constraints, and affordances of the material as used in the user interface. The *addressed senses* refer to the modalities that are involved when interacting with a user interface. Especially unconventional and expressive interaction materials go beyond classical visual and

acoustic stimuli and come along with rich tactile, olfactory or even gustatory stimuli. The *type of use* of the material specifies whether it is applied as a non-functional element in the user interface, e.g., as casing or as decorative element, which means it is not directly used for interaction, or if it is used in a functional way, i.e., by directly using it for interaction, be it as part of input or output of an interface. Furthermore, I address aspects of the materials' *usability* in the application, relating to the materials' ability to support efficiency, learning and satisfaction, which, of course, might play more or less a role depending on the application's purpose. Last, *mapping and technical integration* are included as aspect into our profile, which gives details about how the physical material got interweaved with technology (e.g., sensors and actuators) to become interactive (if applicable) and to merge it into a new physical-digital "texture" (cf., Robles and Wiberg 2010).

Application-Specific Material Aspects on a Macro Level

As last profile part, I present the application-specific material aspects on a macro level. It consists of the *materials meanings* in the application context, the *materials purpose* as well as collected impressions regarding the *evoked emotions* and the *performative role* of the material. Materials can be used in more or less meaningful ways and with varying semantics in different application contexts. This is addressed in the first aspect, *material meanings in the application context*. The *material purpose* names whether a material is used for a rather pragmatic reason (e.g., in order to implement a certain functionality, because of easy availability or processing, as often the case in engineering-driven works) or to realize an expressive interaction (more widespread in art and design-driven works). A further aspect of the profile describes the *emotions a material evokes* when using the interfaces, an aspect that clearly differs depending on subjective experiences of a user interface in situ. Nevertheless, typical emotional experiences can be described as part of the application-specific part of the material profile. A further experience-oriented aspect (and like the emotional level also part of Giaccardi and Karana 2015) is the *performative role* of the material, which relates to how the material influences and encourages actions by users.

3.2.3. The Physicality Representation Spectrum: From Physical to Digital Representations

The third contribution of this framework focuses on the different options to represent physical materials within user interfaces. In HCI, it has always been a topic to use metaphors from our daily environment to facilitate people's understanding of how user interfaces work (see Subsection 2.3.3). However, especially with the rise of ubiquitous computing and tangible user interfaces, there are numerous reasons why it can be useful to directly integrate diverse physical materials into user interfaces (see Subsection 3.1.3). I.e., in order to use and apply certain properties, meanings and emotional connotations of a material within a user interface, interaction designers have a wide spectrum of options from directly applying material aspects physically by integrating the material itself to including only selected aspects metaphorically. The physical-

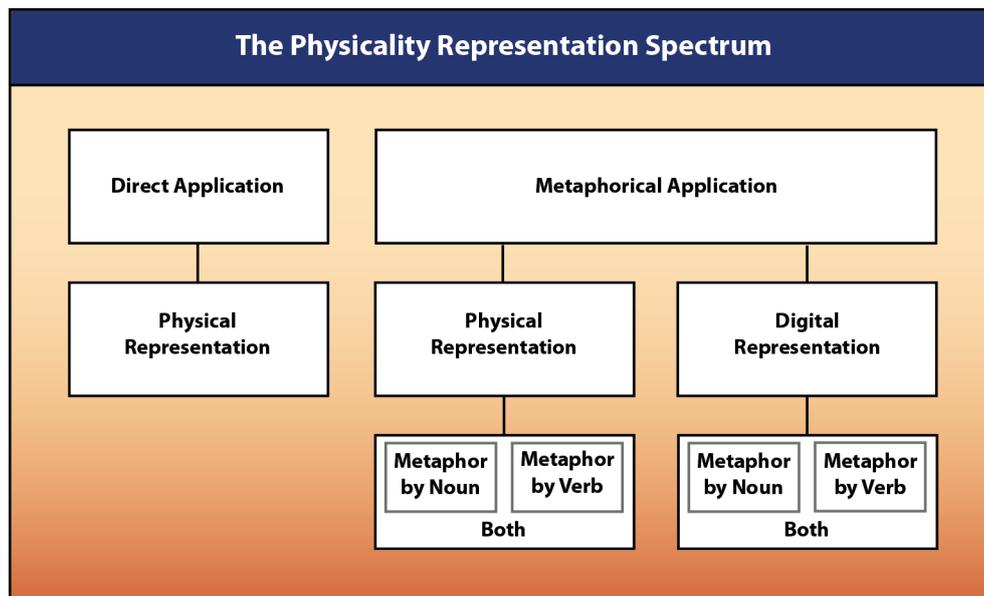


Figure 3.3.: The Physicality Representation Spectrum. Starting from an interaction material, it structures different levels of representations within user interfaces: direct physical representation, metaphorical physical representation and metaphorical digital representation.

ity representation spectrum provides a tool to discuss this increasingly important design space. For example, it serves as a structure to collect user interfaces that all rely on the application of a specific material, but with different – physical, digital or hybrid – representations. The spectrum starts from a physical material and incorporates different ways to apply material aspects metaphorically. Inspired by the distinction between *metaphor by verb* and *metaphor by noun* as applied to tangible user interfaces by Fishkin (2004), our spectrum includes metaphorical applications by verb and noun within physical as well as digital representations. Overall, the spectrum is subdivided into three categories of materials application: *direct application*, *metaphorical application with physical representation* and *metaphorical application with digital representation* (see Figure 3.3). The physicality representation spectrum is also covered in (Döring 2016b), in which it has been applied to plants as interaction material.

Direct Application: Physical Representation

The direct application of properties, meanings and evoked experiences of an interaction material (as described as part of an interaction material’s profile) means that a physical material is directly integrated into a user interface. Thus material aspects are directly physically represented by the material itself, as done in many tangible user interfaces. For example, many ephemeral user interfaces, as described in (Döring et al. 2013a), include the direct application of physical interaction materials like water, soap bubbles, plants or food, and make use of their properties,

meanings and evoked experiences for interaction. E.g., the soap bubble interface (Döring et al. 2012b) makes use of real soap bubbles for interaction. While user interfaces like this form an inspiring and experimental group with a focus on expressiveness, a much more widespread and common interaction design approach is characterized by the metaphorical application of material aspects, as described by the following two categories.

Metaphorical Application: Physical Representation

Tangible user interface elements are often physical representations that apply aspects taken from other physical materials in a metaphorical way, e.g., by applying aspects of shape or typical manipulations for example. I call this category *metaphorical application with physical representation*. If aspects like properties, form factors, or meanings of an original material are metaphorically applied to another physical material, I speak about a *metaphor by noun*. In case a handling or manipulation of a material is physically represented or realized in an embodied way in a user interface without integrating the original material itself, I speak about a *metaphor by verb*. When Bernhaupt et al. (2014) used a soap bubble inspired glass sphere for input for a television system or Ryokai et al. (2010) designed a soft tangible video bubble for video recording and playback, they chose metaphorical applications with physical representations (and, in these cases, applied a metaphor by noun approach), for example. Of course, user interfaces can also integrate both kinds of metaphorical applications (by noun and by verb) in one physical representation.

Metaphorical Application: Digital Representation

Similarly, and with a longer and larger tradition in HCI, physical materials can be applied metaphorically in digital representations, for which graphical user interfaces present the dominating strategy. *Metaphorical applications with digital representation* encompass *metaphor by noun* and *metaphor by verb* strategies. If aspects like properties, form factors, or meanings of an original material are metaphorically applied to a digital representation, I speak about a *metaphor by noun*. In case an action with or manipulation of a physical material is transferred into a different kind of interaction with the digital domain, I speak about a *metaphor by verb*. Again, user interfaces can also integrate both kinds of metaphorical applications (by noun and by verb) in one digital representation. The above mentioned tangible video bubble recording and playback application by Ryokai et al. (2010), for example, included a 2D graphical representation of bubbles, that could be touched “to ‘pop’ the content in order to play back the video message” (Ryokai et al. 2010, p. 2779). This presents a digital representation with metaphor by noun and metaphor by verb. Examples for user interfaces that apply properties of soap bubbles to digital representations can be found in Brade’s and colleagues’ work (Brade et al. 2012) and Khalilbeigi’s and colleagues’ work (Khalilbeigi et al. 2010) for example.

Additionally, different metaphorical applications and physical representations can be combined within one user interface. For instance, in their mixed reality application “Jellyfish party” Okuno

et al. (2003) built a device that allowed real blowing interaction to create virtual bubbles presented in head mounted displays.

3.2.4. Discussion

Addressing materiality aspects of user interfaces is a complex topic. It is important to note that the framework proposed here is not meant to cover all aspects possibly related to materiality and interaction. It rather presents an approach to have a terminology and to make dedicated and also diverse aspects more explicit and easier to overlook for different stakeholders such as HCI researchers, interaction design practitioners, users, teachers or students. Its components could also provide common ground for interdisciplinary teams and participatory design projects, as physical materials, which are generally known and comparably easy to understand, have a central role in both the interaction material profile as well as the physicality representation spectrum. As such, the framework could provide a starting point for a deeper understanding of material-related issues with novel perspectives.

With the interaction material profile, I dissect and structure the different levels on which materials unfold their impact in interaction in order to better understand these details. In the scope of this paper, this structure presents a theoretical approach that can be applied in a number of different ways in future work. Primarily, it is a structure to understand, compare and discuss the role of physical materials in existing user interfaces as part of an analytical material-centered lens to HCI. It can serve as a structure to build a catalogue of selected interaction materials including general material profiles as well as example applications – cf., collections about art materials (Wagner et al. 2010) and materials for design (Alesina and Lupton 2010) – or to build card-based design tools (cf., Deng et al. 2014, Hornecker 2010) as well as to identify material aspects that need further research in material-focused user studies – such as (Häkkinen et al. 2015) about experiencing the elements. Opposed to other approaches, the interaction material profile integrates quantifiable (technical) aspects and qualitative (hermeneutic) approaches about material meaning and experiences. As an analytical approach, the profile does not replace “tinkering” with the real materials (cf., Sundström et al. 2011, Karana et al. 2015, Wiberg 2014), but rather complements this. While we witness a fusion of digital, computational and physical materials (Vallgård and Redström 2007) with increasingly blurred boundaries and novel properties such as temporal form (Vallgård et al. 2015) in HCI, the interaction material profile deliberately focuses on physical materials. To date, the structure has been applied in a first interaction material catalogue about ephemeral and natural interaction materials.

While some aspects covered by the interaction material profile have received much attention within interaction design, for example usability or form factors (cf., Baskinger and Gross 2010), others, like material meanings in cultural contexts and the application context, have not received much attention yet and provide novel insights (cf., Giaccardi and Karana 2015). The profile reveals to what degree a material’s potentials to shape an interaction are leveraged, on a micro level as well as on a macro level. On a micro level for example, it is interesting to see, if a material is used only passively (e.g., as a casing) or functionally. If materials are selected for expressiveness,

they are ideally used functionally within input or output and address multiple senses. The profile allows to compare different approaches regarding these aspects. It also provides views and access points for different kinds of addressers: e.g., for engineers, the micro level might be more relevant (e.g., technical properties, mapping and technical integration), while for media artists the macro level with material meanings might be of more interest.

The presented interaction material profile serves as a structure for a material-centered analysis about how physical material aspects effect HCI from different perspectives and on different levels. The interaction material profile was first of all designed for physical materials. But digital and physical materials increasingly melt into new forms that should also be addressed and, with some adjustments, the profile should work for computational composites and digital materials as well. E.g., for these types of materials “material meanings in cultural contexts” often do not exist and form factors would especially consider temporal form, but overall the structure is applicable. In general, not all aspects in the profile necessarily play a role for each application and material, be it physical, hybrid or digital. With the presented structure, I focus on analyzing applications with one dominating material that coins the interaction, being aware that this might not sufficiently be able to cover works where multiple materials act together. Furthermore, I do not particularly address novel or not yet existing materials (as for example done in Karana et al. 2015). The interaction material profile is explicitly meant to support an analytical view rather than to build a generative approach. The profile combines functional material knowledge with insights gained through experience and interpretation. The descriptions of the experiential material aspects are ideally based on user involvement and real experiences. Alternatively, the macro level of application-specific material aspects has to be discovered empathetically (cf., Prown 1982).

Starting from physical materials, the physicality representation spectrum allows a novel view on previously realized interfaces and could facilitate a material-related analysis. Moreover, it could be suited as a tool to discuss design alternatives in participatory design processes with users, an aspect that has to be explored as part of future work. With its focus on materiality aspects it adds to previous models such as PIBA-DIBA (i.e., “physicality is better at - digitality is better at” Hurtienne et al. 2008), reality-based interaction (Jacob et al. 2008), or blended interaction (Jetter et al. 2014) and allows to discuss a wide range of user interfaces, not only restricted to tangible and embodied interaction. Applying material metaphors is a central strategy in human-computer interaction⁴ and with the growing options for input and output modalities, interaction designers need to better reflect and understand these different representations. Nevertheless, this model does not explicitly address strategies to design for magic (cf., Boll et al. 2008, Rasmussen 2013), that is a central and important aspect of interactive artifacts and that goes beyond mimicking the real world and, as such, beyond properties of physical materials. Of course, designing for magic interactions should also be considered when moving along the physicality representation spectrum.

⁴See, for example, Google Material Design: “A material metaphor is the unifying theory of a rationalized space and a system of motion.” In: Google Material Design. Introduction. <https://material.google.com/#introduction-principles> (last access: October 1st, 2016).

3.3. Chapter Summary

This chapter consists of two parts. The first part (Section 3) presented the *main discourses on material and materiality-related aspects within human-computer interaction*, structured into eight themes. These themes are: (1.) *Conceptualizing Material in HCI*, (2.) *Material-focused Frameworks and Methods*, (3.) *The Computer as Material*, (4.) *Physical Materials for Interaction*, (5.) *Novel and Advanced Materials*, (6.) *Making, Craft, and Do-It-Yourself*, (7.) *Sustainable Interaction Design*, and (8.) *Understanding the Roles of Materials in Practices*. The case studies that will be presented in Chapter 4 contribute to these themes. The first part ended with a short discussion. The second part of the chapter (Section 3.2) introduced and discussed *a framework to understand and inspire how material aspects shape interaction*. It consists of: (1.) *Material Terminology*, (2.) *The Interaction Material Profile*, and (3.) *The Physicality Representation Spectrum*. Aspects of this framework will be applied in the discussion of the case studies in the following chapter.

4. Exploring How Materiality Shapes Interaction: Case Studies and Contributions

To explore how materiality shapes interaction, we conducted a number of case studies and surveys that each contributes to one or more of the material themes of human-computer interaction as introduced in Section 3.1. The conducted and published case studies are presented in three parts. Section 1 deals with two case studies contributing to the exploration of materiality and gestural interaction with physical objects. One case study transferred a classical card game to the digital domain and designed gestural interaction with mobile devices in an interactive tabletop setting. The second case study looked at gestural interaction on an interactive touch steering wheel as automotive user interface. We focus on the question, how aspects of materiality shaped the gestural touch interactions that we designed prototypes for and that we tested in user studies. Section 2 is dedicated to selected design challenges regarding materiality in tangible interaction. Here, the first case study compares a wooden tangible UI to touch interaction in a tabletop-based group setting regarding its effects on collaboration and thus addresses a central material-related design challenge tabletop UI designers face. The second case study explores the decoupling of interaction materials from functionality in tangible interface design and proposes a toolkit approach that enables direct design engagement with the interaction materials by the end user. In the presented approach, we focus on easy-to-handle craft materials as interaction materials. Finally, Section 3 presents a novel class of user interfaces that strongly draws on material properties and material semantics for interaction: ephemeral user interfaces. While this type of interface has been prototyped and presented in many scientific, artistic and DIY contexts, so far there has not been a common understanding and denotation for it. With our work, we set a foundation for this research area by shaping and defining the term "ephemeral user interface", by establishing a collection of ephemeral UIs and by conducting a survey leading to a design space for ephemeral user interfaces. Additionally, we practically explored aspects of ephemeral user interfaces in a case study, in which we created, presented and studied a user interface that uses soap bubbles for interaction.

While we structure our work here into gestural, tangible, and ephemeral user interfaces, all case studies combine tangible and gestural elements. We designed gestural interaction with objects, our tangible interaction includes gestures, and many ephemeral user interfaces we have studied integrate tangible and gestural interaction with ephemeral materials. So, after all, the boundaries between these paradigms are blurred, and it is a matter of emphasis how we classify a certain project. Each of the following sections sets a specific focus that is worthwhile to consider

separately. The case studies were conducted in a variety of different application contexts, i.e. collaborative tabletop games, automotive user interfaces, end-user design toolkits, and artistic and entertainment environments.

4.1. Materiality and Gestural Interaction

Gestures are one prevailing way to interact with computer technology nowadays as they offer natural and rich means for interaction (see Subsection 2.2.1). The term gestural interaction encompasses a wide variety of different gestures from full-body movements to touch-less arm gestures to gestures with devices in free air to pen movements on flat surfaces or touch gestures etc. In our research, we are especially interested in exploring the role of materials in gestural interaction scenarios with interactive surfaces. This means, we focus on tangible gesture interaction (Van Den Hoven and Mazalek 2011), where physical objects are used during gestural interaction. In the following, we reflect on two case studies conducted in different application areas: one is a collaborative game utilizing a tabletop surface, the other one is a multi-touch enabled steering wheel as novel automotive user interface. In both studies, we designed, developed and evaluated gestures for gestural interaction with interactive surfaces: one for combining mobile phone and tabletop interaction and one for using a gesture-enabled steering wheel in the car.

4.1.1. Case Study #1: Gesture-based Mobile Phone Interaction with Interactive Tabletops

The combination of small, personal devices like mobile phones and shared displays for groups like interactive tabletops allows to seamlessly integrate private and public interaction spaces and therefore offers an interesting design space. Among the potentials of this setting is to enable embodied and natural interaction by designing mobile phone based gestures. We explored this design space, which still marks an important challenge in research and information technology products (cf., Kohler et al. 2015), by realizing six different applications that all combined mobile phones gestures and multi-touch interaction on an interactive tabletop. Among the main results of this case study are a set of mobile phone gestures for interaction with a tabletop surface that have potential to be used in more general application contexts as well as insights into how interaction with classical items on tables like menu cards or playing cards can be transferred and integrated into the digital domain. The results of this case study are published in a work-in-progress article at the ACM Conference on Human-Computer Interaction with Mobile Devices and Services (Mobile HCI) 2009 (Sahami et al. 2009) and as workshop contribution of the Workshop on Coupled Display Visual Interfaces (Döring et al. 2010b) in conjunction with the ACM conference Advances in Visual Interfaces (AVI) 2010.

The six applications were developed by teams of 2-3 systems engineering and information systems students in a semester long project and addressed the following application domains: an

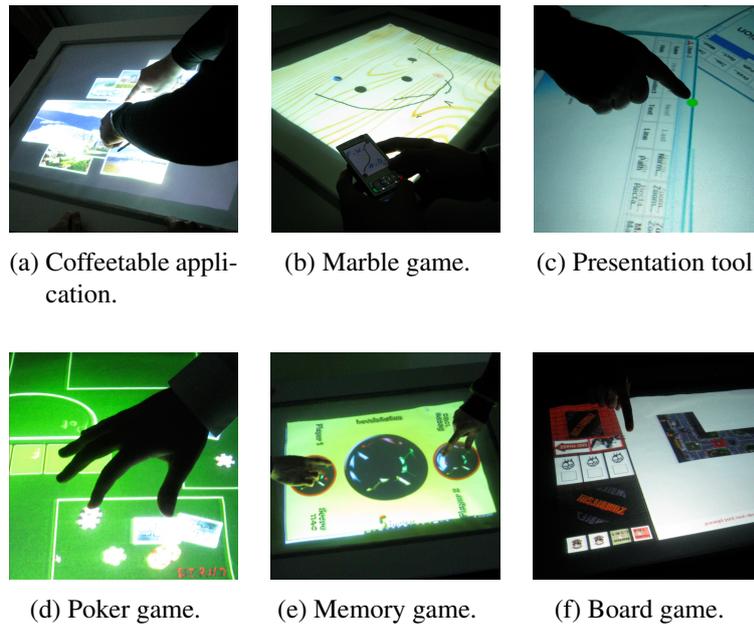


Figure 4.1.: The six interactive applications that combined mobile phone interaction and multi-touch interaction on and around a tabletop surface.

interactive coffee table, a marble game, a presentation tool, a poker game, a memory game, and a board game (see Figure 4.1). Figure 4.2 shows an overview of the resulting set of mobile phone gestures for interaction with a tabletop surface as applied in the six applications. One of the gestures similarly implemented in the coffee table application and the presentation tool was a rotation gesture with the mobile phone to turn a page displayed on the tabletop surface. For this gesture, the mobile phone was held horizontally and by rotating the mobile phone 90 degrees sideways to the left or the right, pages were turned forward or backward respectively. Another useful gesture was shaking the mobile phone up and down. This gesture was used to select an item or to finish an input in the coffee table application, the board game and the poker game. Tilting the mobile phone into all directions, either in a vertical or horizontal start position, was applied as discrete mapping for navigating in a 2D plane (in the memory game) as well as a continuous mapping to tilt a virtual 3D plane on the tabletop surface (in the marble game). In the poker game, mobile phone gestures were implemented to replace interaction with traditional playing cards at the tabletop. When a mobile phone was held vertically, it displayed the deck of cards of the player (see Figure 4.3), when the player turned the mobile phone horizontally, e.g. by putting it onto the table, the cards flipped side and were shown from the back. This mechanism allowed a passive mode, in which personal data was not shown, and an active mode, in which personal data was shown. A central issue when combining different devices is to address how data can be exchanged. In case of the poker game for example, playing cards needed to be placed on the tabletop. In poker, this can be done either with the cards facing up or down. This action was transferred to the digital domain by realizing a throw-gesture, i.e., by moving the mobile phone towards the table, which threw the player's deck of cards onto the tabletop surface. If this

4. Exploring How Materiality Shapes Interaction: Case Studies and Contributions

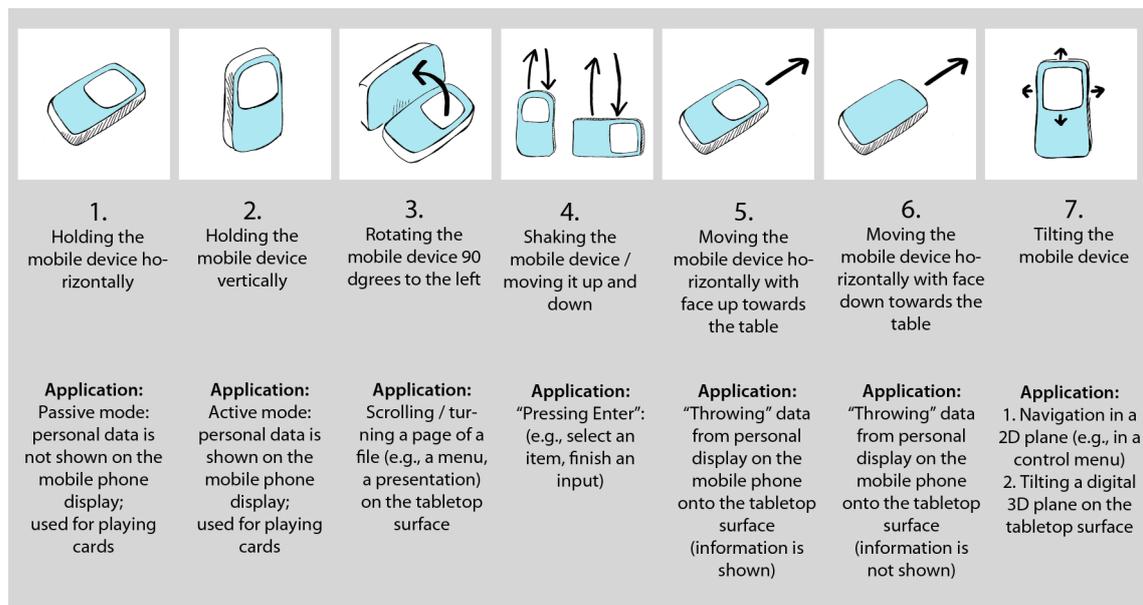


Figure 4.2.: Designed and implemented mid-air gestures with mobile devices.

was done with the phones' face up, the cards were automatically shown, in case the phone faced down the cards were hidden and shown from their back when sliding onto the table.

While we used all six applications to generally explore the design space in informal test settings, we examined the poker game in more depth. In particular, we were interested in comparing traditional playing card and poker table interaction, multi-touch table interaction and mobile phone interaction. We implemented touch interaction on the tabletop for a.) looking into playing cards, b.) checking, c) folding with cards faced up or down, d.) betting and manipulating chips, and e.) moving cards on the table. To look into the cards on the tabletop surface, the players had to cover the displayed cards on the table with their hands to protect them from the view of the other players and then needed to double tap onto the cards. A second double tap turned the cards again. To check, the players had to double tap the tabletop surface (next to any displayed objects like cards or chips). For folding, the displayed cards were touched with a finger and dragged over the tabletop into the center. Betting was done similarly by touching chips and dragging them. Additionally, the game version with multi-touch interaction allowed to split chips into ones with smaller value (e.g., a chip with value 100 into two chips with value 50) by performing a double tap on the displayed chip or. Two chips could be merged by dragging them onto a virtual pile and by performing a long tap (3 sec) on top. As already introduced above, the poker game also integrated mobile phone gestures for looking into cards, checking and folding.

Since we were interested in players' responses to our game versions, we conducted a study with 21 participants (two females) who played the game in groups of three. All groups played the game twice, once in the multi-touch version without phones, once with gesture-based mobile phone interaction. Each game took around 15 minutes, after which the participants filled in a questionnaire in which we assessed for each interaction how well they regarded its execution and



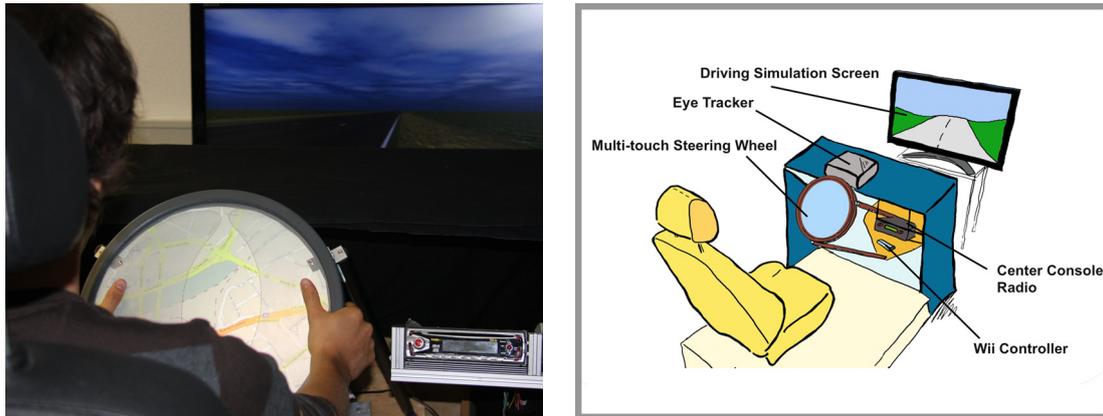
- (a) The personal card deck can be viewed on the mobile phone screen, while the shared game board is displayed on the interactive tabletop surface.
- (b) Chips could be split and merged via touch interactions on the tabletop surface.

Figure 4.3.: Poker Surface: an interactive poker game that combines mid-air gestural interaction with mobile phones with a multi-touch tabletop surface.

how much they liked it (both on a 1 to 5 point Likert scale with “1 = very easy / very much”). Overall, the players liked the novel interactions (i.e., with average like scores below 2.3 for all multi-touch and mobile phone gestures). Additionally, we asked them whether they would like to play a poker game with multi-touch and mobile phone interaction again as well as to provide further feedback. 17 of 21 participants stated that they would like to play Poker at a multi-touch table again. Comparing the popularity of multi-touch and mobile-phone gestures for the commands that were realized in both interaction versions (i.e. looking into cards, folding, checking), we found that, on average, the players preferred the mobile phone gestures for looking into cards and folding over multi-touch, while for checking, they preferred the double tap on the table. Apparently, the users liked the idea to present the deck of cards traditionally in the player’s hands by a mobile phone representing the cards and to perform the traditional card interactions with the phone (e.g., folding/throwing the cards onto the table). So although some of the original material qualities of paper-based playing cards were lost, our transition of real physical objects into the digital domain combined with gestural interaction worked well. Subsection 4.1.3 provides a further material-centered discussion of this case study.

4.1.2. Case Study #2: Gestural Interaction on the Steering Wheel

In this case study, we constructed a multi-touch enabled steering wheel in order to evaluate it as novel automotive user interface. We used the steering wheel surface as additional interactive surface to control infotainment systems in the car and conducted two experiments with users: one study to find suitable gestures for the steering wheel to execute selected commands for a radio and a navigation system and a second study in which we compared performing the gestures to using conventional radio and navigation devices while driving. Both studies were carried out in a lab-based driving simulator setup. Central and original results of this case study are a set of gestures for multi-touch steering wheels as well as the finding, that performing touch gestures compared to using conventional devices reduces the visual demand while driving. These results are published in a full paper in the Proceedings of the International Conference on Human Factors



(a) A participant is using the interactive map application on the multi-touch steering wheel while driving in the driving simulation setup.

(b) The test apparatus for the comparative study: next to the multitouch steering wheel, we integrated conventional middle console devices for comparison. An eye tracker was used to analyze participants' gaze behavior.

Figure 4.4.: The multi-touch steering wheel: setup and test apparatus.

in Computing Systems (CHI) 2011 (Döring et al. 2011). While the details of the case study can be found in the paper, we summarize the main aspects and results in the following.

Based on the principle of frustrated total internal reflection (Han 2005), see also Subsection 2.1.4, we built a multi-touch enabled steering wheel (see Figure 4.4). The construction consisted of a rotatable stand with a steering wheel rim measuring 70 cm in diameter and attached hardware to facilitate input and output: infrared LEDs embedded in the rim, a webcam for tracking the finger touches, a projector for visual output on the steering wheel and a Wii remote for tracking the steering wheel rotation. Webcam, projector and Wii remote were attached to the foot well of the construction. The surface of the steering wheel consisted of an acrylic plate with a thin layer of silicone above and a top layer of tracing paper as projection surface. Based on our observations during pilot studies, we restricted the interactive area on the steering wheel to two areas close to the edges of the steering wheel. This ensured that the drivers could leave their hands at the rim while performing gestures with the thumbs. In order to conduct studies in a driving environment we integrated the steering wheel in a driving simulation setup with a three by two meters large projection in front of the steering wheel and a real car seat behind it (see Figure 4.4). We used standard driving simulation software during the user studies (i.e., CARS (Kern et al. 2008) in the first study and the Lane Change Test (Mattes and Hallen 2008) in the second study.

With our first study, we developed a suitable gesture set for interacting with typical info- and entertainment systems in cars while driving. We proposed 20 commands for music player, navigation system, map and list interaction and applied the method of user-defined gesture sets (see Wobbrock et al. 2009, and Chapter 2) by inviting 12 participants to perform a gesture for each of the 20 commands in randomized order while driving in our driving simulation setup. So in total, we collected 240 gestures, which we evaluated and clustered by frequency. Depending on

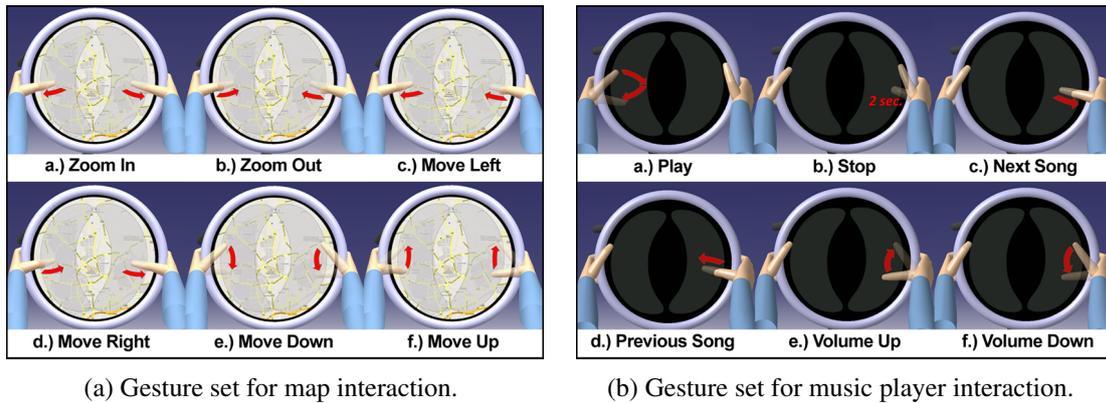
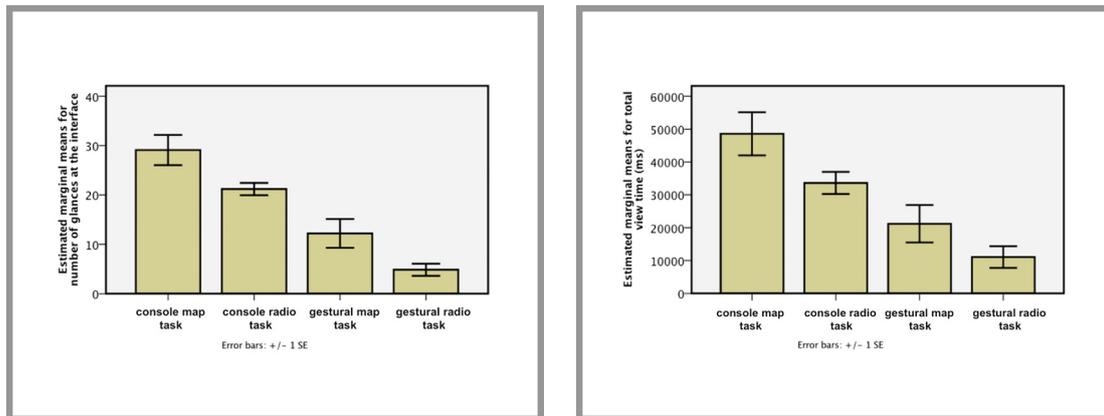


Figure 4.5.: Selected gesture set for the multitouch steering wheel. The gestures were designed based on a gesture elicitation study.

the command the degree of agreement varied. One of the aspects that influenced this fact was to what degree material metaphors could be applied to the gestures. This aspect will be further addressed in the discussion below. We compiled a resulting gesture set by taking the most frequent suggestion for each of the commands.

For our second study, we selected a set of 12 gestures out of these, 6 for using a music player, 6 for map interaction and compared them to conventional device interaction in the car while driving (see Figure 4.5). We additionally added a standard middle console radio, a loudspeaker and a navigation system to the driving simulator for this purpose. The visual output for the gesture-based map interaction was displayed directly on the steering wheel surface. To assess the visual demand of the interaction while driving we additionally attached an eye tracker above the steering wheel to analyze the participants' gaze behavior (see Figure 4.4b). The study was conducted with 12 participants, who had to perform all four study conditions (gesture radio, gesture navigation, console radio, console navigation) twice. Each run was dedicated to one condition and lasted three minutes. Additionally, the participants performed reference drives without additional interaction in the beginning, after the first round of the four conditions and at the end of the study. In our evaluation, we assessed three dependent variables: the number of actions performed in each run, the driving performance data, and the data on visual demand consisting of number and duration of user's glances at the interface. In brief, we obtained the following results (see also Figure 4.6). First, users performed more actions with the gestural interfaces than with the console interfaces (1st trial map interaction: 17.2%, 1st trial radio interaction: 18.3%, 2nd trial map interaction: 22.2%, 2nd trial radio interaction: 18.0%). Second, regarding driving performance, we found a main effect for radio interaction with less lane deviation in the gestural condition and no effect for map interaction. Third, we found a quite big reduction in visual demand for the gestural interaction: gestural radio interaction caused 77.2% less glances and 67.1% less time spent looking at the interface. For gestural map interaction the number of glances were reduced by 58.1% and the time spent looking at the interface was reduced by 59.7%. In the next section, I will analyze the resulting gestures and discuss how the steering wheel as interaction object and the users' previous experience with physical materials in other domains guided the interaction.



- (a) Estimated marginal mean number of glances at the interface by condition across both trials. Marginal means for the radio task control for the effect of frequency of actions.
- (b) Estimated marginal mean time spent looking at the interface by condition across both trials. Marginal means for the radio task control for the effect of frequency of actions.

Figure 4.6.: Results on the visual demand when using the multitouch steering wheel vs. conventional middle console devices.

4.1.3. Discussion

In our two case studies on gestural interaction with objects we combined functional devices with gestures. Thus, our interaction materials, the mobile phone and the steering wheel, affected what and how gestures were performed in many ways. The two case studies both present explorations of the design space of tangible gesture interaction (Van Den Hoven and Mazalek 2011), as they explore different configurations. These are composed of, for example, the interaction materials (the mobile phone as custom device versus the self-constructed steering wheel), the affordances and constraints of the objects (a free-movable in-hand object versus an attached wheel that can only be moved by turning), the kinds of gestures realized (mid air free movement versus touch gestures on the surface), the tasks the gestures are applied to (primary versus secondary), as well as the methods the gesture interactions were designed with (expert-based versus user-defined design). In the following, I will discuss each case study along selected aspects of the material-centered framework as presented in Section 3.2.

Within the application contexts we studied in our mobile phone gesture explorations, I will focus on the mobile phone gestures realized within the poker game here. These are inspired by using playing cards in classical card games: holding the mobile phone vertically shows the playing cards, turning the device horizontally hides the cards' faces, and moving the mobile phone horizontally towards the table throws the cards onto the table. The metaphors by verb (*physicallity representation spectrum: metaphorical application – physical representation – metaphor by verb*) applied here, metaphors that are based on the manipulations of playing cards, ease the understanding of the interactions and were particularly enjoyed as being fun by our participants. By applying them, we translated interaction qualities with physical playing cards to the digital

domain. Instead of applying a metaphor by noun, i.e., by realizing objects that directly represent playing cards (or even by using playing cards themselves), we used the generic mobile phone as interaction material. The mobile phone, established as universal personal small-scale device, can be regarded as a *computational composite material* that comes along with a number of properties that make it attractive for developers as well as users. From a developers perspective, it is convenient that mobile phones offer integrated input, output and network capabilities (e.g., accelerometer sensors, vibration, a (touch-) display, bluetooth and WiFi connectivity; which together present its *technical properties*) and *form factors* that afford comfortably holding the device in one hand. These aspects facilitate the development of mid-air gestures with mobile phones. As the phone normally is held in the palm of one hand, the gestures are influenced by movements that are comfortable for the corresponding hand and arm. This resulted in gestures like shaking the hand, rotating it left or right, tilting the palm, holding the hand vertically as well as horizontally or moving the arm forward. Moreover, mobile phones have the advantage of a large flexibility, one phone can show many cards for example. One device and one gesture can be applied for exchanging a variety of data in very different application contexts. As mobile phones are widespread as personal devices, they are very well suited as private devices in settings combining private and public displays. So, from a materials perspective, one of the characteristics of this approach for applying card games to the digital domain is enhancing the mobile phone as generic interaction material, which already exists as the user's personal device, and designing interaction techniques that can be generically applied to other contexts of use. This means, the playing cards as content could easily be exchanged by other data (e.g., text documents, pictures or videos) and the card-throwing metaphor could also work for transferring these to the table.

When we compare the interactions with paper cards to the ones possible with mobile phones from a *micro perspective*, many aspects of the fine-grained tactile manipulations are not possible when using a standard mobile phone as material. For example, in card games, players might like the feel of the cards, bend them or riffle them in certain ways. Standard phones with plastic covers offer less softness as paper as well as less tactile manipulations. While the focus in this case study was on *functional aspects* of the interactions, such *non-functional aspects* have not played a major role in the materials selection. So if the design focus should be on allowing rich tactile manipulations of the interactions materials, more specific devices with material properties that allow for more flexibility could be interesting as a next step, e.g. devices such as the Paper-Phone (Lahey et al. 2011) or ReFlex (Strohmeier et al. 2016). From a *macro perspective*, it is obvious that the selection of the mobile phone as interaction material was rather for the reason of *pragmatics* than *expressiveness*. Although having only a young history of cultural appropriation, the mobile phone as material has evolved to a meaningful personal device (“our most relevant identity-kit”, Belk 2013, p. 492). Nevertheless, as a gestural object that presents playing cards it is used in novel ways, where established *material meanings* are not used for the interaction. Nevertheless, this does not exclude that new material practices might evolve over time. Thus, the material here first of all mainly unfolds its potential on a micro level, especially through its technical properties and affordances. Moreover, it presents a generalizable interaction solution that allows transferring it to other application domains.

Our second case study, in contrast, focuses on a very specific application scenario with self-constructed special purpose *computational composite* combining computational and physical ma-

materials: the multi-touch steering wheel that supports the execution of secondary tasks during car-driving. In this case we have the special situation that the steering wheel presents an interaction object, which materiality shapes the primary as well as the secondary tasks. While the automotive steering wheel is to a large degree standardized (e.g. the diameter), the multi-touch extension required new functional properties (e.g., the tracking of surface touches). As no devices were ready available, we had to construct our own custom device that was based on multi-touch technology. Here we focused, similar to the mobile phone gesture study above, on materials to realize *functional aspects* of the prototype (e.g., the finger tracking) rather than non-functional aspects (e.g., a diverse texture). Thus, we applied currently common DIY multi-touch tracking technology and chose an FTIR setting with a flat paper-based projection surface as top layer. On the *macro level of interaction* this means that the material purpose of this early multi-touch steering wheel prototype was designed with *pragmatics* in the focus, not *expressiveness*. This, of course, also is due to the safety-critical task of driving. The multi-touch setting first of all had to work and the steering wheel had to have a feeling similar to a regular steering wheel, e.g., regarding size, shape and rim for example.

When analyzing the resulting interaction with the *physicality representation spectrum*, we find two different aspects in which materials shape the interactions on a micro level. First of all, the technical properties and affordances of the steering wheel itself, and second, the metaphors taken from the material world that are applied in the gesture set itself. The steering wheel as interaction object guided the interaction by its specific material affordances and constraints. Being attached and rotatable and having a rim for hands to hold on, it guides the hands' positions as well as movements to perform the primary driving task and at the same time defines the setting for the secondary tasks. The condition that the gestures should be performed while driving constrained the gesture design space to both hands at the steering wheel rim. While we originally had not planned to focus on thumb gestures, they emerged as very useful in our pre-studies, as the participants could easily leave both hands at the steering wheel all the time. Moreover, the thumb-gestures were easy and comfortable to perform, they could be executed very briefly, and they still offered a quite large gestural design space as both thumbs could be used together for the gestures. In our case study, we studied gestures for controlling a music player and a digital map. Thus, it is interesting to analyze to what degree participants chose gestures that were inspired by interactions with physical materials. For the "move map" commands, the resulting gestures were directly inspired by moving physical maps and adjusted to the thumb movements. This is an example for spatial mappings that are directly made from interaction with physical objects to the digital domain. The zoom gestures are also based on experiences with physical materials, as they imagine a stretchy material that can be spread, which enlarges the content shown. Here, we find a *metaphor by verb* applied (cf., Wobbrock et al. 2009). This gesture was known by many participants already, mainly from using it on mobile phones, so that most users could transfer it to this novel use context and device. In the music player gesture set, interactions were less connected to manipulations of physical materials. The resulting "stop" gesture was simply abstract. The dominating "play" gesture was based on the play symbol on classical radios, thus here we find a symbol transferred from the material device that is digitally presented in our setting. The gestures for "volume up/down" and "next/previous song" also are based on experiences from manipulations in the material world, but are so basic that they do not relate to specific materials. Rather, they are part of image schema, "abstract representations of recurring dynamic patterns of

bodily interactions that structure the way we understand the world” (Hurtienne and Israel 2007, p. 130) – see also Subsection 2.3.3) – which, metaphorically applied and transferred to gesture design, result in mappings such as “increase volume is up, reduce volume is down”. Looking at the strategies the participants applied when searching for gestures, we see that transferring physical interactions directly or metaphorically to the digital domain is a preferred approach. Generally, these gestures also result in higher agreement among the users compared to gestures with abstract or symbolic nature. Analyzing both case studies from a materials perspective, we find a number of aspects how materials shape gestural interaction on the micro and macro level of interaction. We have looked at two distinct scenarios for gesturing with objects: mid-air gestures with the mobile phone and touch gestures at the steering wheel. In both cases, the materiality of these objects guided and constrained the gesture design space. Additionally, for the design of the gestures, known manipulations from the material world were transferred to the digital domain through metaphors, both, by developers in the first case study (e.g., putting cards on the table) and by the users in the second study (stretching a material for zooming, moving upwards to increase volume). Both studies showed a high user acceptance on the one and suitability of the gestures for the context of use on the other hand. In these case studies, which both present early explorations of the relating design spaces, we focused on *micro level material aspects*, such as technical properties that provide the needed functionality as well as affordances and constraints. Future work could additionally explore non-functional aspects (e.g., more diverse touch textures and opportunities for fine-grained tactile manipulations) and the *macro level of interaction* (e.g., evoked emotions) in more depth.

4.2. Materiality and Tangible Interaction

We explored materiality and tangible interaction in two settings. The first case study contributes to a timely and currently evolving field of research: end-user design for tangible user interfaces. This is an important field, as product customization as well as comprehensive DIY-projects get increasingly feasible and popular. The development goes hand in hand with a growing DIY and maker movement, the availability of personal fabrication tools for example in fab labs (Gershenfeld 2005), and novel product chains that make use of digital product blueprints and separated material instantiations of the products (cf., Schmidt et al. 2011). End-user design of tangible products already is possible but usually still demands comprehensive skills, often including electronics, programming, CAD software and knowledge about fabrication machines. In our case study we explored a toolkit approach, in which we separated the user interface from the application logic, so that users could focus on the interaction materials and at the same time easily relate them to functions. In our case study, we used craft materials for the shell. The second case study focuses on material considerations for UI designers. It inquires the potentials of a wooden tangible tool in the context of a collaborative tabletop game by comparing it to a digital tool that is used via touch. As such it exemplarily addresses a very timely and important design challenge UI designers who are involved with tangible and multi-touch interaction have to face: touch or tangible interaction (see also Hancock et al. 2009, Lucchi et al. 2010, Tuddenham et al. 2010)? The results provide insights into how different interaction materials affect the collaboration. Again,

I will first introduce our case studies and, subsequently, discuss the related material-centered insights these provided.

4.2.1. Case Study #3: End-User Design by Physical Composition

End-user design for tangible user interfaces is an application context of rising importance when looking at the growing DIY and maker scene and at the potentials of personal fabrication as well as novel distribution chains in manufacturing that allow a high degree of end user customization for products. From an engineering perspective, the separation of the user interface from the application logic is a useful approach that has yet not been realized for tangible user interfaces although it has a long tradition within software engineering. We propose this separation by developing a concept that contains an inner core with a system on a chip, the necessary software and a projector camera unit and, separately, an outer shell composed of passive components like a cover and tangible UI elements as well as a display surface (see Figure 4.7a). Thus, our concept allows a simplified hardware (ex-)changeability, more and easier opportunities to (re-)design a device by end users regarding functionality, appearance and user interface, and it addresses the needs for a better sustainability of used physical parts, as the single modules can be replaced or used again in a different configuration. In this case study, we realized a prototype toolkit that combined a functional core with a freely shapeable passive shell via vision-based tracking of components. We built a toolkit to design a functional alarm clock without wiring and tested it in a design workshop with 15 participants, including people with and without design background. In the workshop, we assessed the general utility of our approach as well as how much the participants liked it and compared it to paper prototyping via questionnaires. Among the main results was that the participants were able to design and assemble alarm clocks with the toolkit and that the majority preferred the physical prototyping method for designing interactive devices. Some participants found paper prototyping more useful for early design tasks and combined both approaches. This case study was published as a work-in-progress contribution in CHI Extended Abstracts 2010 (Döring et al. 2010a). We furthermore discussed the overall context of trends in end-user design and customization of smart devices as well as driving factors of personal fabrication in an article published in IEEE Pervasive computing (Schmidt et al. 2011).

Figure 4.7 shows the concept and vision of our toolkit to create an alarm clock. As outer shell, we constructed a wooden box with an opening in the front for the interaction panel that could be freely designed (see Figure 4.8). For the panel itself, we provided fitting foam boards, tracing paper as projection surface and a variety of 3D-printed UI elements like knobs, sliders and wheels that could be attached to the foam board. The core of our tools consisted of a pico projector that projected via a mirror from the back onto the interaction surface as well as a camera, used for tracking the UI components. The latter needed to be supplied with small fiducials by the users in order to be identified and detected in their actual state. In our prototyping setup, the computer that provided the according software modules was still externally connected, although, for future versions, an integration would easily be possible. In our evaluation workshop, we additionally provided crafting materials like paper, tracing paper, pens, scalpel knives, scissors, glue, scotch tape, sticky notes and differently shaped colored stickers. We deliberately selected crafting and

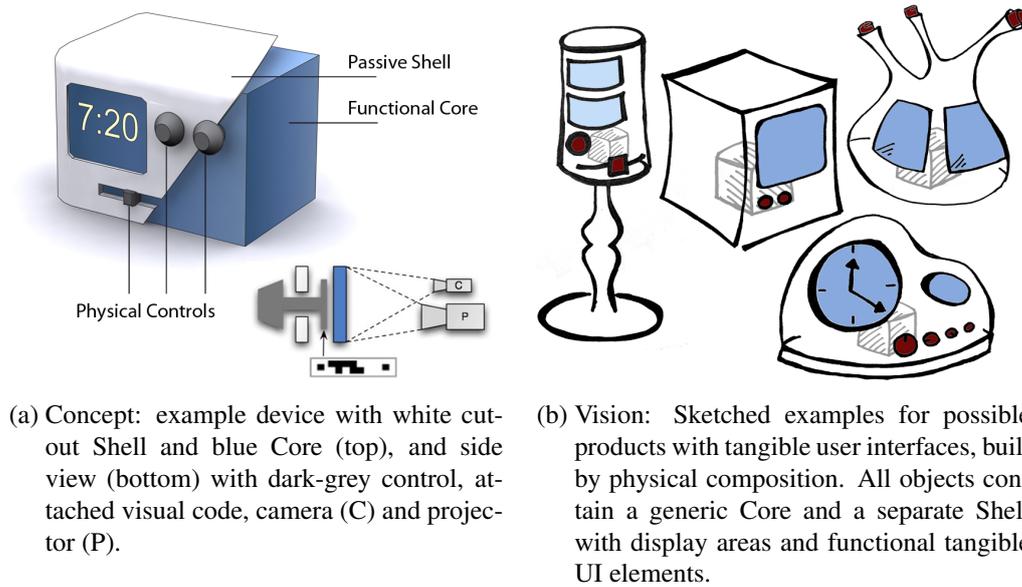


Figure 4.7.: A toolkit to support end-user design by physical composition.

paper-based materials to offer a low threshold for participants with different backgrounds and at the same time offer as much as possible freedom in the design. The craft materials could be combined with white 3D-printed UI elements, in our example made from plastic (Acrylnitril-Butadien-Styrol, ABS) filament, that could be easily clipped to the foam board. In future, end users could select and modify these UI elements based on the digital blueprints and print them themselves (e.g., at home, in a local fab lab or via a 3D print service order) in their preferred material. Due to time restrictions this aspect was not part of our first evaluation of the concept. To design and construct an alarm clock with our box toolkit, users could think about the functionality they wanted and select from a set of prepared functions our software provided (e.g. show digital or analog clock, set timer, set sleep function, snooze button etc.). To design the according user interface they needed to decide about the UI elements and locations and to cut openings into the foam board. E.g., for the display, an opening needed to be cut and covered with tracing paper. Thus, displays did not need to be square and sliders could be wavelike for example. The physical prototyping approach did not require any programming. Figure 4.8 shows examples.

We organized a design workshop with 15 participants including people with and without design background (see Figure 4.9 for impressions of the workshop setting and created prototypes). The workshop lasted 7.5 hours in total and contained two two-hour design sessions as well as introduction, presentation and discussion time. The participants were grouped into four teams of three to four members, who all were given the task to design an alarm clock. Two groups started with paper prototyping, two groups with our toolkit. In a second round they used the other approach, respectively. In the beginning, they filled out a demographics questionnaire, and at the end of the workshop, each participant filled out a workshop questionnaire containing a subset of the USE questionnaire (Lund 2001) questions regarding paper prototyping and our physical prototyping approach as well as comparing both approaches. Overall, all participants regardless

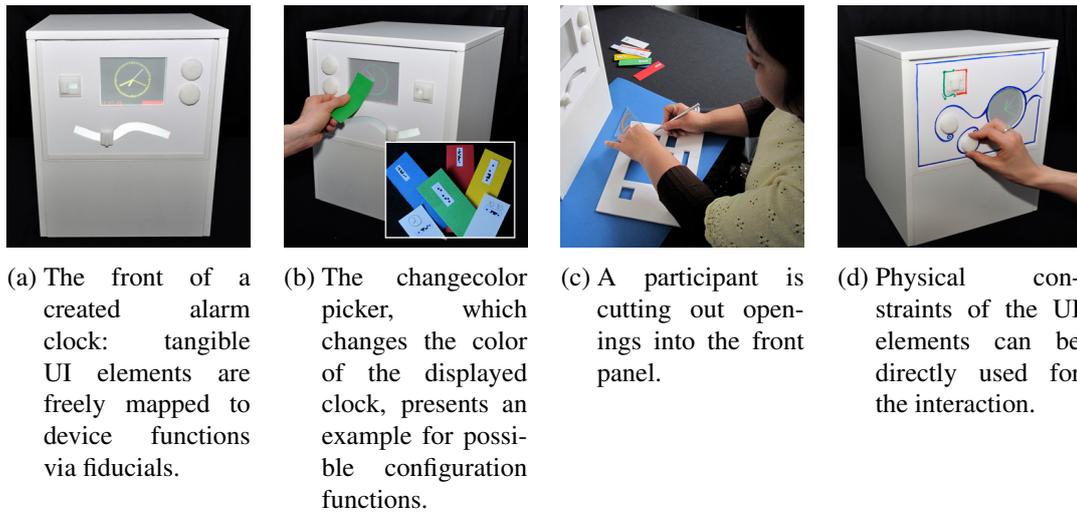


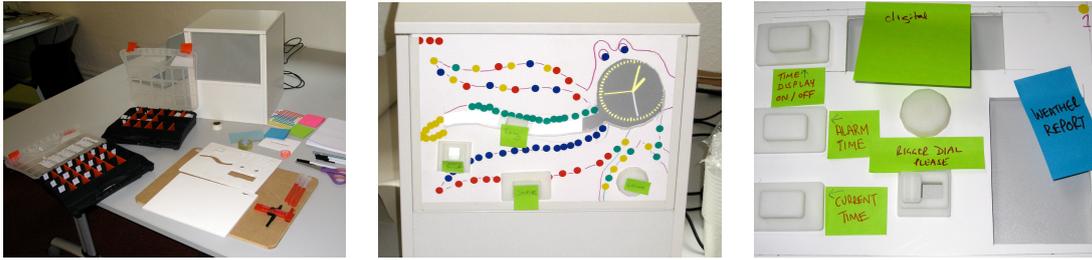
Figure 4.8.: Proof-of-concept toolkit to build an alarm clock with tangible user interface.

of with or without design background were able to understand our concept and use the tool to build a functional device. Participants liked the physical prototyping approach because they could “see it work” immediately. Nevertheless, many found paper prototyping still easier to use for an early prototyping task and we observed that some participants combined both approaches (cf., Figure 4.9c). This tendency encouraged us in our approach to use simple craft materials for this early design task. For a full realization of our concept more sophisticated and still easy-to-use interface materials (e.g., 3D-printed or laser-cut) would be appropriate. This will be discussed further in the next section.

4.2.2. Case Study #4: Comparing a Tangible and a Digital Tool for Collaboration in a Tabletop Game

In this case study, we explored how different versions of tools, tangible and multi-touch, enable collaboration in an interactive tabletop-based group game. We were especially interested in how tool use differed between the two versions and how they affected collaboration. We addressed this critical design challenge for tabletop settings by extending a lab-built tabletop game called “Futura” with two visualization tools and a corresponding visualization feature.¹ The two tools, which had the shape of magnifier glasses, were realized in two versions each: a tangible version with objects made from wood and a digital graphical version that was displayed on the tabletop surface. In a user study with 45 participants, who played the game in groups of three, we collected quantitative and qualitative data about the groups’ collaboration and tool use. We analyzed the data along four themes from the literature of computer-supported collaborative learning and

¹The game “Futura” was developed by Alissa Antle and colleagues (cf., Antle et al. 2011), the visualization tools were realized by Tess Speelpenning. For more information, see also: <http://www.antle.iat.sfu.ca/Futura/> (last access: October 2nd, 2016).



- (a) Workshop setting: the participants' workplaces were provided with a toolkit box, a fiducial assortment box, camera and projector as well as 3D-printed UI elements and craft materials.
- (b) Example of a functional prototype of an alarm clock designed by end-users.
- (c) A workshop result combining paper prototyping with the functional toolkit approach.

Figure 4.9.: Impressions of the created physical prototypes from the design workshop.

tangible user interfaces: *objects of negotiation*, *access points*, *physical constraints* and *awareness*. Among the main results of this study are that the tangible tools enhanced the feeling of ownership, which led to more player announcements and a better group awareness compared to the tool use of the touch-based tool. The results of this case study are published in a full paper at Interact 2011 (Speelpenning et al. 2011).

The tabletop game we used in this study, *Futura – the Sustainable Futures Game*, is a multiplayer game, in which three players need to collaborate in order to preserve the environment and meet the needs of the growing population (see Figure 4.10a). Each player had a different role: one was in charge of food, one of shelter and one of energy. All players needed to place their resources on the interactive game board and to understand positive and negative effects of their actions regarding the development of the environment and the population over a time span of many years in order to win the game. This demanded the collaboration of all three players. To foster collaboration between them, we added a visualization layer that showed the impact the resources placed on the board had on the environment and the population as colored overlay over the game world. This layer could be triggered and removed by two different tools that we compared in this study: two tangible user interfaces made from wood (see Figure 4.10b) and shaped as magnifier glasses, one for environment impact and one for population impact and two digital magnifier glasses of the same size and with the same icons that were displayed on the tabletop surface. The tangible magnifier glasses normally rested on the rim of the table and needed to be put onto the interactive tabletop surface to show the corresponding impact layer, one at a time. Lifting the magnifier glass from the table finished the layer visualization and resumed the game. On the contrary, the displayed magnifier glasses were shown at fixed positions and used by touch. Resuming was done by a separate resume button.

We were interested how the tool uses differed and how these affected the collaboration between the players. Thus, we conducted a lab study with 45 players who played the game in groups of three. All 15 groups played the game three times in each condition (multitouch and tangible) in



(a) The tabletop game Futura with graphical presentations of magnifierglasses.



(b) Wooden magnifier glasses.

Figure 4.10.: The collaborative tabletop game Futura.

counterbalanced order (either first three times in the multitouch condition and then three times in the tangible condition or vice versa). Each game lasted approx. 5 minutes. During the study we collected questionnaire data about demographics, learning outcome, perceived collaboration and tool use, etc. Additionally, we measured game performance and score as well as frequency and timing of tool use. Through qualitative observational notes and video we assessed physical and verbal interactions between the users. Overall, we had 204 tool uses in total in our study, 108 in the tangible condition and 96 in the touch condition. All groups used both tools in both conditions, while tool use varied between groups from minimal 3 to maximum 20 usages. We found no significant differences in frequency of usage between conditions, but we did observe differences in tool handling. While in the touch condition resuming was often done by a different player that initiating, often without checking with the other players, in the tangible condition initiating and resuming by the same person occurred significantly more than in the touch condition (77% vs 56%). This may be explained by the concept of ownership (Beggan 1992). We also found better tool awareness in form of tool announcement in the tangible condition. Many players preferred the tangible tools (26 vs. 17). So overall, the study showed that tangible and digital tools can have different effects on collaboration. Our results indicate that physicality of tools may enhance ownership and facilitate group awareness.

4.2.3. Discussion

The central idea of tangible interaction is that the integration of physical materials facilitate human-computer interaction. In our two case studies, the materials employed as tangibles are directly used for the interaction, thus they are *functional* elements of the user interface. We integrated them into the systems by adding fiducials and corresponding vision-based tracking algorithms (*technical integration*).

In our end-user design case study we chose the interaction materials in accordance to a craft and DIY setting (*technical properties; material meanings in cultural contexts*). As the materials were de-coupled from the functionality, principally any materials could be used for interaction, which provided a large design space. From a technological perspective of the toolkit, this a powerful

approach. In the current toolkit version, mapping and tracking is done by fiducials (*mapping and technical integration*). This is only a first step, as it yields some limitations. I.e., the materials used for interaction need to have enough space on the back to attach fiducials, we can only track in a 2D space and we cannot track gestures (with or without objects) for example. Moreover, finding the correct fiducial stickers (they were assigned to a dedicated function or UI element) and attaching them at the desired locations turned out to be cumbersome for some of the participants. Therefore, we would recommend a vision-tracking system without fiducials in future scenarios. This could also allow unconventional interaction approaches and materials and a greater variety of form factors, e.g., to integrate moldable materials or fluids for interaction for example. The materials and the setting we chose in our design workshop addressed an early prototyping scenario for a design sketch. In this phase, paper-based and craft materials are classical materials. As Tholander et al. (2012) have shown when exploring material agency in interaction design tasks, the provided design materials actively inspire the design process, so it matters what materials are provided, not only what materials are possible to integrate from a technological perspective (*performative role*). From our experience, this should fit the stage of the design process as well as the intended users. While our concept also targets at the customization and design of final interactive products and end users, we addressed an early design task and included professional designers in our first exploration. While we mixed designers and non-designers in our workshop, these two user groups have different knowledge and skills that need to be addressed. If used later in the design process when the basic mapping and layout has already been thought of, our toolkit should integrate more sophisticated UI materials, also in combination with digital blueprints and possibly longer production times, e.g., with means of personal fabrication.

In this case study on tangible interaction, the setup generally allowed users to integrate any materials as interaction materials. While we aimed at designing an alarm clock, we did not choose to provide materials specifically suited for an alarm clock, but rather wanted to start with a generic approach. Our materials selection was inspired on the one hand by classical crafting as we wanted to provide a low-threshold access for users without a technical background and on the other hand by materials currently widespread in personal fabrication, here in form of 3D-printed control elements (*material meanings in cultural contexts*). The incorporation of materials and associated strategies and processes currently evolving in personal fabrication allows a very versatile toolkit approach for end-user design and customization. In our early toolkit prototype, we provided raw, unshaped materials as well as ready-to-use interface elements printed from plastics in various shapes. So overall, users needed to play around with the materials, understand how they could be used for interaction, and they also needed to have some craft skills, e.g. to cut fitting holes into the front panel (*technical properties; material-specific form factors*). Furthermore, they needed to understand how they could map the interaction materials to certain functions. This mapping task, which in tangible interaction addresses how material qualities are used in the interaction, normally is part of the user interface designer's tasks. While in our workshop, participants were generally able to handle this task, it is relevant to further conduct research on how much freedom users generally want or if they prefer a preselection of suitable materials for certain functions (*mapping and technical integration*). In our workshop, we also provided paper for simple paper prototyping and many participants argued that they really liked the simple use of paper as design material, although not interactive at this point. This again shows that simple physical materials

often support tasks very well and that it can be very valuable to integrate them into interactive systems.

In the Futura study, we used two wooden artifacts in the shape of a magnifier glass with handle that fit well into a person's hand and compared it to a graphical magnifier glass of about the same size. The interaction with the wooden tools was quite simple: they usually rested on the passive rim of the tabletop and lifting one up and putting it on the active tabletop surface triggered a special visualization, putting it back resumed the game. The players easily grasped this idea and all groups used the tool. The context of use, a multi-player tabletop game, influenced the choice to integrate a wooden tool insofar as wooden game elements are typical in classical board games (*material meanings in application context*). Overall, it was especially the magnifier's shape that mattered here: it should be easy to be grasped, robust, lightweight, represent a magnifier glass, and it needed to have a flat background and a fiducial on the back to be detected (*application-specific form factors*). Nevertheless, the wooden tools were aesthetically appealing, had nice painted symbols, and the fact that most users preferred the tangible tools over the graphical touch tools, is likely also influenced by these aspects. Especially the better tool announcement in the TUI condition probably has to do with the interaction in 3D space compared to the simpler and faster touch interaction on the surface: lifting the physical tool and placing it on the table takes longer, can be, for example, done half way and interrupted for group announcement, and is much better visible by all participants. Against our assumptions, passing around the tool nearly did not happen. Moreover, we found that often the same person put it away again, which indicated a sense of ownership induced by the physical object. Apparently, the *performative role* of the physical magnifier tool differed in comparison to the digital magnifier tool.

In the Futura study we compared different instances on the *physicality representation spectrum* against each other: while the tangible tool physically represented a magnifier glass through its shape (*metaphorical application - physical representation - metaphor by noun*), the touch version presented a picture of a similar looking magnifier glass (*metaphorical application - digital representation - metaphor by verb*). Both tools applied the meaning of the magnifier glass only metaphorically: instead of providing a real or virtual lens and enlarging an area of focus, the tools contained symbols of persons or trees and could be used to show additional information in form of a heat map containing information about the state of the population or pollution in the game. The magnifier glass metaphors helped to understand that the tangible tool could be put on the tabletop surface. It also gave a cue that more details could be expected but it did not match the original concept in some cases, e.g., the location where it was put did not matter for the visualization. Nevertheless, users understood the concept in both conditions. Overall, what we can take away from this study are insights into how different material representations affect the interaction.

4.3. Materiality and Ephemeral User Interfaces

Ephemeral user interfaces (EUIs) are a class of UIs, in which the interaction is guided to a large degree by the materials used. EUIs contain at least one UI element that is intentionally integrated not to last, like food, fog, water or soap bubbles etc. Especially since user interfaces for entertainment have become an emergent field and user experience has increasingly received central attention beyond the demand for efficient use of a system, ephemeral user interfaces have been designed and developed in art, design and research contexts for many years. While these interfaces yet have not been discussed under one common term, we conducted a survey, collected examples, grouped them under the term "ephemeral user interface", defined it and analyzed the example systems and their corresponding design space from a materials perspective.

The results from our studies are valuable for HCI regarding a number of aspects. First, ephemeral user interfaces provide very powerful examples how material qualities can directly guide an interaction, often only by its physical characteristics (e.g., material affordances) or by its semantics. Insights about these effects can either be applied to user interfaces by directly using these "expressive" materials themselves, by transferring the gained experiences to other materials (e.g. smart materials), or by a metaphorical application to software and hardware systems. Second, user experience aspects get increasingly important when designing and developing human-computer interaction. This is also due to the manifold application areas beyond supporting office work. Especially in leisure, music, home or other entertainment application areas, user experience crucially contributes to the success of a user interface. Ephemeral user interfaces generally have a strong focus on user experience as the applied materials for interaction are mostly very expressive, often multi-sensory and in many cases emotionally touching. And third, persistency of data or even of interaction elements is not necessarily essential for every system. There is a discussion in HCI that claims more ephemerality, as the ever-lasting persistency of data and devices around us leads to an information overflow that is impossible to deal with (cf., Bannon 2011). A popular application that realizes a limited data persistency is snapchat², a messaging tool where pictures and videos are deleted after they have been presented to the recipient once for a defined short time frame.

Our contribution to this field of research includes a definition and conceptual foundation for ephemeral user interfaces as well as establishing a design space for EUIs. Furthermore, we practically explored this UI class in a case study with a soap bubble user interface. The next subsections summarize the associated publications on ephemeral user interfaces and explain their contributions to interaction design and materiality.

4.3.1. A Design Space for Ephemeral User Interfaces

We introduced, defined and discussed the novel concept of ephemeral user interfaces in a full paper presented at ACM TEI 2013 (Döring et al. 2013a) and in a feature article in the ACM

²<http://www.snapchat.com> (last access: October 24th, 2016).



(a) Solar Eclipse.



(b) Minimum Monument by Néle Azevedo, sculptures made from ice (courtesy of Néle Azevedo, www.neleazevedo.com.br).

Figure 4.11.: Humans enjoy ephemeral events. While aspects of human life are ephemeral in general, some events or materials evoke a strong feeling of ephemerality, making a particular moment special, often connected to a certain aesthetics.

Interactions Journal July/August 2013 (Döring et al. 2013b). In these publications we provide a design space for ephemeral user interfaces based on an analysis of 50 user interfaces and installations as well as corresponding publications and videos presented or published in HCI research or art contexts. This research presents a novel and original contribution, as these user interfaces never have been discussed under one common term before. Moreover, the insights into material usage for ephemeral UIs result in a number of directions for future work including design tools for material-focused user interfaces, ephemeral smart materials and time-based user interfaces as well as ephemerality as metaphor for hard and software design. We furthermore extended this work by providing a unique collection of ephemeral user interfaces online available on www.ephemeral-UIs.org. Building a foundation for a new research program, it has been picked up by recent research work (cf., Kwon et al. 2015, Seah et al. 2014, Giaccardi and Karana 2015, Fuchsberger et al. 2015).

The term “ephemeral” (Greek *ephēmeros*) literally means “lasting only one day” and depicts temporally restricted phenomena or species, e.g., the mayfly (ephemeroptera), non-permanent waters, or the changing position of planets (ephemeroptera). It furthermore connotes a certain aesthetics, the beauty of the moment that often comes along with a strong multisensorial experience (cf., Figure 4.11). Vagueness and fluidity or transition are also aspects that are part of the ephemeral. In this sense water is regarded as an ephemeral material par excellence (see also Buci-Glucksmann 2003). Furthermore, in cultural studies the term ephemeral is used to describe phenomena that belong to the triviality of everyday life, e.g., the latin word for dairy literature is “ephemerides”. We believe that ephemeral user interfaces are suitable to represent and implement all these aspects in human-computer interaction. In our design space, we discuss along many example user interfaces how this can be done.

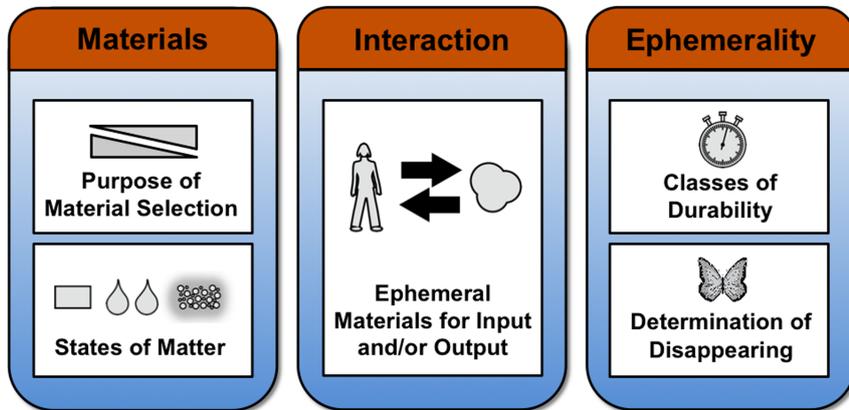


Figure 4.12.: Overview on the design space for ephemeral user interfaces.

We define “ephemeral user interfaces” as follows:

“Ephemeral user interfaces are a class of user interfaces that contain at least one UI element that is intentionally created to last for a limited time only. The durability of the UI element is determined by its intrinsic material properties in combination with its surrounding ecosystem. While their ephemeral UI element(s) exist(s), ephemeral user interfaces provide a rich and multisensory user experience. They may deliberately be designed to offer only partial or imperfect user control”. (Döring et al. 2013a, p.77).

Our definition focuses on temporal aspects, multisensory user experience and limited user control. In ephemeral user interfaces, temporality is used in a meaningful way for the interaction. The material qualities and aesthetics of interface components play a dominant role for the user experience, as they often provide multisensory feedback (due to the material properties) as well as carry embedded meanings from other contexts (which refers to the materials’ meaning). Meaningful examples for UI components are the elements as natural materials like water, air, earth, and fire. Many ephemeral user interfaces are perceived as being poetic, and we found a strong focus on emotional response and sensual experience as recurring theme. Engaging and poetic interactions do not necessarily need to be precisely controllable as manifold examples show.

The design space structures and addresses central aspects of ephemeral user interfaces and provides a terminology for (a.) *materials for ephemeral UI elements*, (b.) *interaction* and (c.) *aspects of ephemerality*. Figure 4.12 gives a top level overview of the design space. In the following, we give a brief insight into the dimensions of the design space and highlight some example ephemeral user interfaces, for more details see (Döring et al. 2013a).

One interesting aspect of materials for ephemeral UI elements is the purpose of their selection for the user interface. On the one extreme this can be strongly guided by a material’s meaning, like done in “ThanatoFenestra” (Uriu and Okude 2010), a buddhist altar using a candle’s flame

for input realized by the Japanese UI designers Daisuke Uriu and Naohito Okude. When the candle is lighted, a photograph of a dead relative is displayed and when it flickers, a new picture is shown. As the candle and the atmosphere connected to it fit well into the Buddhist practices and have certain cultural connotations, which are used for the interaction here, the material selection clearly was motivated by the materials meaning. One the other end of the spectrum is a selection mainly influenced by a material's properties, an approach usually taken from a classical engineering perspective. Nevertheless, this can also be done with unusual materials for interaction, like in Noisy Jelly, an electronic music instrument that uses different shapes of jelly with different concentrations of salt, realized by the french designers Raphaël Pluinage and Marianne Cauvard (Pluinage and Cauvard 2012). In this interface, the varying conductivity of the jelly and its different colors and easy malleability were utilized to generate and visualize different sounds. So presumably, the material properties played a bigger role here for the material selection than the jelly's meaning as food. While often a design evolves from either end of the spectrum, in other cases, both, the material properties and semantic's equally played a role in the material selection process. Our continuum supports the reflection of this aspect. Another dimension of our design space classifies the user interfaces regarding their material's states of matter: solid, liquid and gas. A further focus lies on the material's use for input, output or both (for a categorization of example user interfaces by *states of matter* and *interaction* see Figure 4.13). Many ephemeral user interfaces use ephemeral materials for output only, for example "bit.fall" by Julius Popp (Popp 2004), a water-curtain-based display that presents words taken from news on the internet for very short time spans. These UIs can allow no or implicit user interaction or indirect interaction. The already mentioned musical instrument Noisy Jelly presents an example where ephemeral materials are used for input only, thus it realizes an indirect interaction. When ephemeral materials are used for input and output, the input and output space merge, which allows direct interaction. An example interface is "IceWall", a multi-touch enabled wall made from real ice blocks with integrated projection (Virolainen et al. 2010, Ventä-Olkkonen et al. 2014). We furthermore analyzed how ephemeral user interfaces realize temporality and found three different approaches: by natural phenomena (e.g., falling water drops due to gravity), by user interaction (e.g., destroying soap bubbles), or by system trigger (e.g., the computer varies a surrounding condition). When we looked at the durability of ephemeral UI elements we found six classes of durability from ultrashort (minutes) (e.g., Bit.Fall by Popp 2004) to long (months to years) (e.g., PlantDisplay by Kuribayashi and Wakita 2006) and one that realizes flexible durability depending on the surrounding conditions (e.g., "IceWall" by Virolainen et al. 2010).

So overall, our design space discusses many dimensions of ephemeral user interfaces that shed light on this novel class of user interface but also on material aspects of user interfaces in general. While we focus on ephemeral phenomena for HCI here, we believe that the presented dimensions play a role beyond temporally restricted user interfaces.

4.3.2. Case Study #5: The Soap Bubble Interface

To practically explore the concept of ephemeral user interfaces in more depth, we built a soap bubble interface, in which we used soap bubbles as handles for input and as projection surface

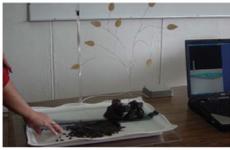
Interaction Type / States of Matter	Ephemeral Materials for Output only (Indirect Interaction)	Ephemeral Materials for Input only (Indirect Interaction)	Ephemeral Materials for Input and Output (Direct Interaction)
 <p>Solid</p>	 <p>Plant Display (Kuribayashi and Wakita 2006)</p>	 <p>Noisy Jelly (Pluinage and Cauvard 2012)</p>	 <p>Ice Wall (Virolainen et al. 2010)</p>
 <p>Liquid</p>	 <p>Water Games (Parés et al. 2005)</p>	 <p>Water Interface for VR (Diaz et al. 2003)</p>	 <p>Soap Bubble Interface (Sylvester et al. 2010)</p>
 <p>Gas</p>	 <p>Murmur (Rydarowski et al. 2008)</p>	 <p>Thanato Fenestra (Uriu and Okude 2010)</p>	 <p>Interactive FogScreen (Rakkolainen et al. 2005)</p>

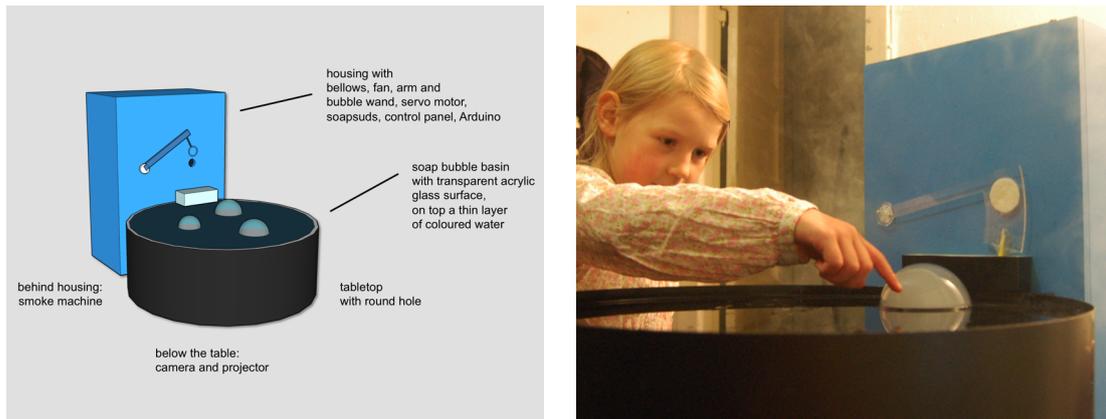
Figure 4.13.: Examples of ephemeral user interfaces structured by “states of matter” and “interaction type”.

for output (see Figure 4.14). Soap bubbles depict a very interesting material for interaction as they come along with very distinct material meanings on the one hand but also very special material properties on the other hand. As such, they form a perfect ephemeral material to explore and discuss how materiality can naturally shape and constraint interaction by its meanings and properties. We called this concept “material-based interaction constraints” (Döring et al. 2012b). Moreover, soap bubbles provide a rich user experience which lead to a diverse “material driven user engagement”. The “Soap Bubble Interface” was published and demoed at TEI 2010 (Sylvester et al. 2010) and “Mensch und Computer 2010” (Döring et al. 2010c). In total, it has been explored in six public and semi-public settings by more than 100 users. Furthermore, users’ emotional responses to it were investigated in a lab-based user study. Insights derived from user interacting with the installation regarding *material-based interaction constraints* and *material-driven user engagement* were published in a CHI Work-in-Progress publication 2012 (Döring et al. 2012b), results from the lab-based study were published at the Workshop “Be-greifbare Interaktion” at “Mensch und Computer 2015” (Döring et al. 2015).

While we focused on the effects of soap bubbles as handles for input, some ephemeral user interfaces can be found, where soap bubbles are used for output (some realized before, some realized after our first presentation): among these are the ambient displays “The use of soap bubbles”



Figure 4.14.: The Soap Bubble Interface: a user moves a smoke-filled soap bubble in order to influence the room illumination.



(a) System setup of the Soap Bubble Interface. (b) A girl interacting with a fog-filled bubble on the surface.

Figure 4.15.: Setup of the Soap Bubble Interface.

(Jauk and Ranzenbacher 2005) and “Shaboned Display” (Hirayama and Kakehi 2010), and “Bubble Cosmos” (Nakamura et al. 2006), the musical instrument “Ephemeral Melody” (Suzuki et al. 2008), and two ambient displays combining fragrance with soap bubbles “FragWrap” (Kyono et al. 2013) and “SensaBubble” (Seah et al. 2014).

The Soap Bubble Interface consists of a soap bubble basin with a transparent acrylic surface and a top thin layer of colored liquid as well as a housing with self-constructed soap bubble generator and integrated fog machine behind (see Figure 4.15). When the soap bubble machine is used via a small control panel to generate single bubbles, either filled with fog or plain, in desired sizes, these fall onto the basin, where they float as half spheres on the liquid layer until they burst. Below the basin is a camera to track the size and location of the bubbles as well as a projector for visual output on the fog-filled bubbles (not used in all versions). Thus, the amount, location and sizes of the bubbles on the surface can be used to control an application. Users can generate soap bubbles and once they float on the surface, they can try to move them around, typically by one of three different interaction techniques that we observed (see Figure 4.16): by gently touching a bubble with a wet finger and by moving it around, by bending forward and blowing a bubble into a desired direction, or by creating airflow with the hands or an object. The techniques vary in their degree of preciseness but also in the degree of needed body movement and skillfulness. All three interaction techniques are purely inspired and guided by the specific material properties of soap bubbles. During the different setups of the system, we explored different applications and

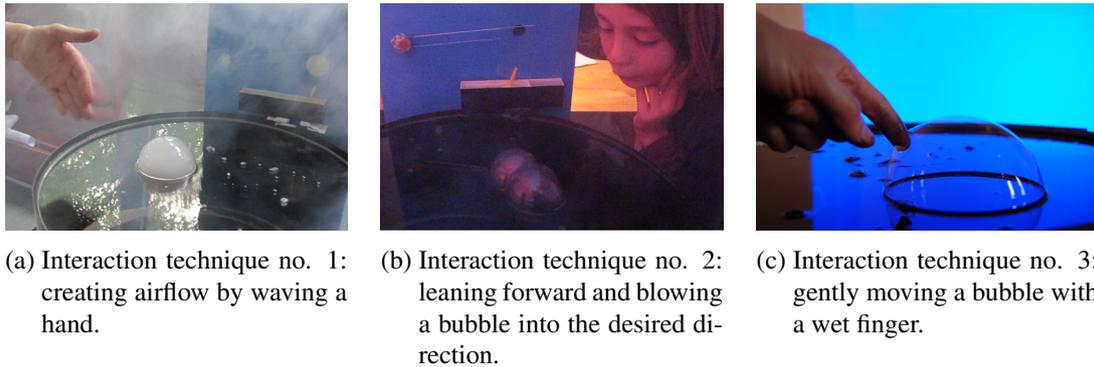


Figure 4.16.: Different interaction techniques for the Soap Bubble Interface.

interaction mappings. In the setup most often applied, the users could control ambient lights and sound by moving the soap bubbles on the surfaces. To realize the tracking of the soap bubbles and provide the relevant parameters for the interaction mapping, we use circle tracking with openCV³, extract the parameters and provide them in the Open Sound Protocol (OSC)⁴. The ambient light application is realized in VVVV⁵ while the sound control happens in Pure Data⁶.

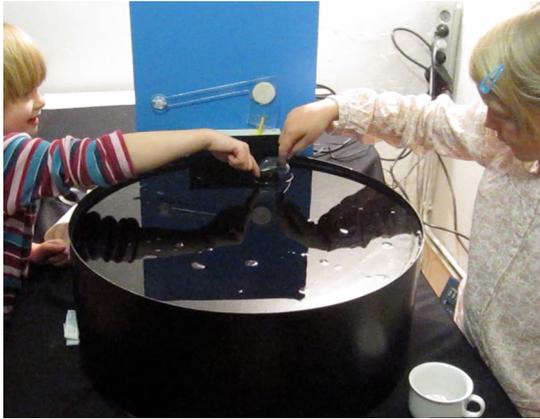
Soap bubbles are a nice material for an ephemeral user interface due to their natural transience, their beauty and poetic connotation and their limited controllability that fosters a playful, challenging and fun interaction. Soap bubbles are popular among young and old, and extensive literature and documentation about their properties and cultural meanings can be found in art, science and literature, in research as well as in everyday media. Bubbles are made from soapy water and form almost perfect spheres due to the surface tension water has. They float through the air, can easily be burst or burst by themselves, are elastic and when they hit a liquid surface or each other they connect and change their shape. All these characteristics foster a playful interaction with them. Moreover, soap bubbles are perceived as very fascinating and poetic, they act as symbols for vanity for example, or build “in-between spaces”, neither real nor virtual. These properties and meanings of soap bubbles as well as habits connected to them naturally shape the interactions with the bubbles. This happens implicitly, and it is among the goals of this work to better understand how material qualities can be explicitly applied for interaction. I have already mentioned the different interaction techniques that evolved due to material-based interaction constraints. To explore aspects of a “material-driven user engagement” we furthermore observed how the soap bubbles as interaction materials shaped the user engagement with our installation (see Figure 4.17). We structured this along four themes Dalsgaard et al. (2011) have identified for engaging users in public settings: *cultural practices*, *physical conditions*, *the content* and *social practices*. In our observations, we found a strong influence of the interaction material regarding all themes, for details see (Döring et al. 2012b).

³<http://opencv.org> (last access: October 15th, 2016).

⁴<http://opensoundcontrol.org> (last access: October 30th, 2015).

⁵<http://vVVV.org> (last access: October 15th, 2016).

⁶<https://puredata.info> (last access: October 15th, 2016).



(a) Two girls using the installation together. Here, they try to move a bubble jointly.



(b) Two users, spontaneously performing a music and light performance.

Figure 4.17.: Material-driven user engagement with the Soap Bubble Interface.

In order to examine real soap bubbles as input means in an interactive game, we combined the soap bubble interface with a projection at the wall that visualized an underwater game environment (see Figure 4.18). To investigate how the interaction with bubbles differed from the interaction with stable and more conventional input materials, we conducted a lab-based user study with 10 participants (Döring et al. 2015). In this study, we compared the above-described setting to a setting with transparent plastic half spheres (see Figure 4.19). We were interested in investigating how the emotional response, the UX and the ways of interaction differed between both interface instances and applied the User Experience Questionnaire (Laugwitz et al. 2008) and the PANAS-X (Watson and Clark 1999) as well as analyzed videos of the sessions. Among our results was that, although the game was harder to play with the soap bubbles, positive affect was rated significantly higher for the real bubbles. Our observations and the video analysis revealed furthermore that the interaction was also much more diverse and more playful with the soap bubbles. The users were very creative in trying out novel interaction techniques and in involving their whole body in order to gently move the bubbles. This study was published in (Döring et al. 2015).

4.3.3. Discussion

Ephemeral user interfaces generally put a strong focus on material qualities for interaction. The central materials are generally used for *expressivity*. When we introduced ephemeral user interfaces we looked at the interaction materials beyond the common view on materials' surfaces and shapes. We looked at the materials' states of matters for example, and next to solid materials, we also considered liquid and gaseous materials. Ephemeral user interfaces focus on a holistic multisensory experience of the materials, beyond simply touching a surface. Users can get wet for example, they get cold fingers when touching an ice wall, they can move inside of fog or they can eat part of the user interface after an interaction. The ephemeral materials can be used as *functional or non-functional materials* for an interaction. Generally, the material plays a central

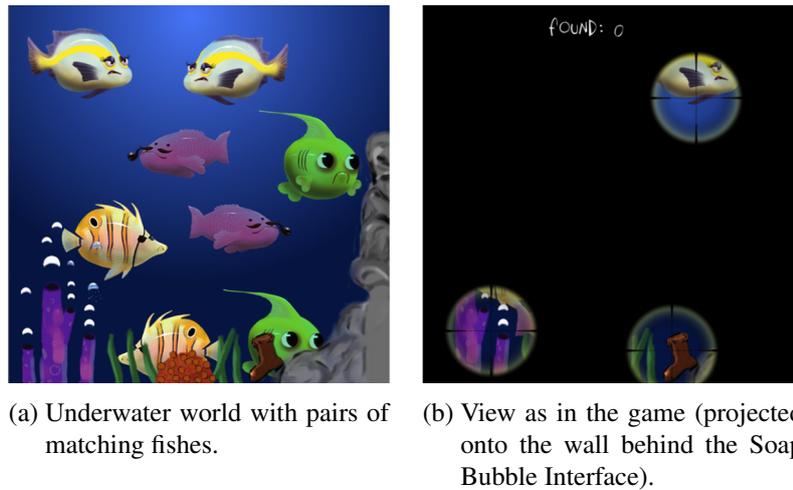


Figure 4.18.: Graphical output of the game. The fishes were hidden beneath a black layer and needed to be uncovered by moving soap bubbles to the according locations.

role for the interaction. Ideally, the material provokes and shapes the interaction by its *technical properties* and *cultural meanings*. In many cases, the materials motivate a playful interaction, which can lead to ways of interaction that might not have been thought of or have not been intended by the designer in the beginning. In case of the soap bubble user interface for example, we had not thought about waving as an interaction technique. But when presenting the installation to people, many preferred waving the bubbles into the desired direction as a more unobtrusive interaction technique than blowing or touching. Moreover people came up with playful usages of the installation like making figures with the bubbles or using it in pairs together, e.g., by touching one bubble together at the same time or by playing a blowing game from two opposite sides of the setup. All these usages were not specifically intended nor implemented by the system, but the soap bubbles as materials afforded and allowed these (*material- and application-specific form factors*). This is one of the advantages we see when we build systems that incorporate everyday physical materials. There are many implicit aspects that altogether shape the interaction and influence why we like or dislike something. Usually, the usages and manipulations of materials are so rich and diverse that it is impossible to imitate all these in a digital artifact. Often, many aspects and qualities are lost in digital artifacts, while when we integrate physical materials, we can maintain these qualities and uses and at the same time add computational power. The soap bubbles as interaction materials, for example, burst after a while, which can be a different span of time dependent on many complex influences like the consistency of their soap film, the surrounding airflow, the weather etc. next to interaction by people. This richness gets lost when we replace the real soap bubbles by plastic spheres, which we did in the comparative lab study to explore the effect on the users' emotional responses.

We have seen that ephemeral user interfaces put a focus on a multisensory user experience (*addressed senses*). In most user interfaces, usability, accuracy, efficiency or even determinism are not so relevant. They rather focus on being playful and entertaining. Thus, typical *application contexts* for ephemeral user interfaces are entertainment and leisure applications like media



(a) Real soap bubbles as tangible bubbles for input. (b) Plastic half spheres as tangible bubbles for input.

Figure 4.19.: We compared real bubbles and plastic bubbles as input handles for an interactive game.

consumption, e.g. watching movies, cf., “Thermal Interactive Media” by Mine et al. (2011), or looking at photographs, cf., “VortexBath” by Watanabe (2007) as well as musical instruments. Especially the latter can be found with many different materials like fire, cf. “Satan’s Calliope” (Kristen 2007), water, cf., “Hydraudrilos” and “Hydrophon” by Mann et al. (2011) or “Tangible Sound” by Yonezawa and Mase (2000), ice, (cf., Mann and Janzen 2012), soap bubbles, cf., “Ephemeral Melody” by Suzuki et al. (2008) or “Wubbles” by Berthaut and Knibbe (2014), and jelly, cf. “NoisyJelly” by Pluvinage and Cauvard (2012). Obviously, ephemeral interaction materials fit well to music making, as the already sensory user experience of listening to music gets further leveraged by using sensory materials for music making. Furthermore, the often unusual materials in this context generally evoke surprising effects, very suitable for entertainment. We found many examples following this strategy, i.e., to bring exciting but simple materials into a new application context where they typically are perceived as strange materials, e.g., in the case of “NoisyJelly”. On the other extreme there are ephemeral user interfaces, in which the materials are specifically selected to fit the context of the interface: for example, when water is applied as projection surface in the bathroom, cf. “VortexBath”, when plants are inserted as displays in the living room, cf. “PlantDisplay” by Kuribayashi and Wakita (2006) or “Botanicus Interacticus” by Poupyrev et al. (2012), when an ice wall is deployed as multitouch surface in an outside setting in the Finnish winter, cf. “IceWall” (Virolainen et al. 2010, Ventä-Olkkonen et al. 2014), or when a candle is used for interaction in an altar setting, cf. “ThanatoFenestra” by Uriu and Okude (2010). Especially the water interfaces often take place in or are suited for public space, often tying in with traditional fountains but providing novel interactive experiences, e.g. “Water Games” by Parés et al. (2005), “Appearing Rooms” by Hein (2004), “Bit.Fall” by Popp (2004), “DataFountain” by Van Mensvoort (2005), or “Rain Room” by Koch et al. (2012). Many of these ephemeral user interfaces stem from art contexts and explicitly broach the issue of ephemeral materials in combination with computer technology. A very large application area for ephemeral user interfaces are ambient displays, as on the one hand the subtle materials fit the usage at the periphery, cf., “DataFountain” by Van Mensvoort (2005) or “Interactive FogScreen” by Rakkolainen et al.

(2005), and on the other hand, their transience can be applied to naturally compensate the problems of information overflow, cf., “Bit.Fall” (Popp 2004) or “Murmur” (Rydarowski et al. 2008). Some ephemeral user interfaces are explicitly used or discussed as input and/or output devices for or virtual environments, e.g. Interact with virtual nature (Díaz et al. 2003), and games, e.g., “Lollo” by Murer et al. (2013), “Water Games” by Parés et al. (2005), or “Pumpktris” by Pryor (2012). While we started to use our Soap Bubble Interface as entertaining device to influence light and music (Sylvester et al. 2010), we also used it for input in an interactive game (Döring et al. 2015). Many aspects of the bubbles are very suited for game control as well as output, which we already had seen during our observation studies. A further application context for the user interface could be therapeutic contexts, where blowing or moving bubbles can be used as engaging interaction technique.

In our design space for ephemeral user interfaces, we focused on the exploration of integrated natural materials that do not last into user interfaces. We did this because we wanted to shed light on the power, impact and beauty these materials have and how this can shape interaction with digital technology. We believe that there is still much to learn for interaction design about how this can be done and what aspects influence the resulting interaction. But although we focused on the direct integration of physical materials here, we are aware that the overall design space for ephemerality and digital systems is much bigger. In line with the arguments of Jacob et al. on reality-based interaction (Jacob et al. 2008), it is not in all cases useful or possible to integrate real world physical objects and materials into applications, but it is useful to start from reality which implies starting from the materials we looked at here. While we do argue that the real materials bring a wealth of values, be it functionally or non-functionally applied in the user interface, that are often impossible to replicate in a computer system with standard hardware, this design space can actually be regarded as continuum from an integration of real physical materials to a simple graphical representation that takes ephemerality and decay as concept (see the *Physicality Representation Spectrum*, Subsection 3.2.3). In between are computational objects that are meant to represent natural physical materials and the physical application of certain properties of an original material only (e.g., in form of a prop in a certain shape). This is often done to help potential users to better understand an interaction based on an underlying metaphor. On a much more abstract level, this metaphorical application can also take place in a 2D graphical representation. When we look at plants as interaction material, for example, we find a number of user interfaces that use real plants for input and/or output, e.g. plantDisplay (Kuribayashi and Wakita 2006), Botanicus Interacticus (Poupyrev et al. 2012), Interactive Plant Growing (Sommerer and Mignonneau 1993), or Akousmafflore (Lasserre and Met Den Ancxt 2007). An approach that physically presents a flower by other materials and maps selected properties of flowers is the Robotic Plant implemented by Holstius et al. (2004). Nevertheless, aspects of decay are not part of this concept. On a much more abstract level and detached from the physical appearance of plants are metaphorical applications of plants in graphical 2D presentations that apply a flower metaphor (e.g., Martin and Ju 2010). With soap bubbles as interaction materials, we also find instantiations on different abstraction and material levels. Next to the user interfaces with real soap bubbles mentioned above there are approaches where soap bubbles are represented physically by different materials like plastic half-spheres (Döring et al. 2015) or a glass sphere (Bernhaupt et al. 2014). Projects where soap bubbles were graphically displayed in three dimensional space can be found in “the Bubble User Interface” of a television system (Bernhaupt et al. 2014) and

in the mixed reality application “Jellyfish party” (Okuno et al. 2003). On a more abstract level, selected properties of bubbles can be found applied as “soap bubble metaphors” in several 2D visualization approaches (cf., Brade et al. 2012, Khalilbeigi et al. 2010), in these cases picking up the physical properties of soap bubbles when merging.

4.4. Chapter Summary

This chapter provides an overview on the conducted case studies on gestural, tangible and ephemeral user interfaces. To explore *materiality and gestural interaction* (see Section 4.1), we conducted two case studies with self-constructed prototypes: *gesture-based mobile phone interaction with interactive tabletops* and *gestural interaction on the steering wheel*. For both setups, we designed and evaluated gesture sets that were guided and constrained by aspects of materiality. In a discussion we dissect and analyze these different aspects. Furthermore, we dedicated two case studies to *materiality and tangible interaction* (see Section 4.2), one focusing on an *end-user toolkit* and one *comparing tangible and digital tool use in a collaborative tabletop setting*. Again, aspects how materiality shaped interactions in both case studies are discussed. Finally, we defined and explored *ephemeral user interfaces* (see Section 4.3) as a novel class of UIs that contain at least one UI element that is intentionally integrated not to last. We provided a *design space for ephemeral user interfaces*, presented and evaluated *the Soap Bubble Interface* and discussed central aspects of materiality of ephemeral user interfaces.

5. Conclusion

This doctoral dissertation, composed of the thesis (part one) and 15 publications (part two), presents foundations of a materials perspective on human-computer interaction and related case studies on gestural, tangible and ephemeral user interfaces, in which we explored empirically how materiality shapes interaction on different levels. This chapter summarizes the contributions of this dissertation and discusses future work.

5.1. Summary of the Contributions

After a motivation for a materials perspective on human-computer interaction, an overview on the research contributions and the methodology, the thesis outline, and a list of included publications in Chapter 1, I presented the HCI background this work is embedded in in Chapter 2, presenting interaction terminology and concepts. Chapter 3 sets the theoretical background and presents evolving material themes in human-computer interaction (Section 3.1) as well as my own application of material terminology and two novel structural approaches on materials as part of user interfaces (Section 3.2). Chapter 4 presents an overview on carried out empirical artifact-based research work that is covered in the included publications and discusses the results along dedicated aspects deriving from the material themes and the structural approaches presented in Chapter 3. This empirical work contributes to the three subareas: *materiality and gestural user interfaces*, *materiality and tangible user interfaces*, and *materiality and ephemeral user interfaces*. Finally, this Chapter 5 gives a summary of contributions and discusses future work.

Overall, the results of this work encompass theoretical, survey, artifact, and empirical research contributions on materiality and human-computer interaction. They can be summarized as follows (see also Section 1.2 in the introduction chapter):

1. A survey on evolving **material themes in HCI** (*survey contribution*, see Section 3.1 and publications in Subsections 6.1.1 - 6.1.3). The identified eight themes are: (1.) *Conceptualizing Material in HCI*, (2.) *Material-Focused Frameworks and Methods*, (3.) *Physical Materials*, (4.) *The Computer as Material*, (5.) *Novel and Advanced Materials*, (6.) *Making, Craft and Do-it Yourself*, (7.) *Sustainability and Interaction Design*, (8.) *Understanding the Roles of Materials in Practices*. They focus on different angles of a materials perspective on HCI, and together they shape a novel structure on this developing research field, leading to the identification of crosslinks, open issues and potentials of transdisci-

plinary approaches. The work of this thesis contributes novel insights to each of these eight themes.

2. A **framework** to understand and inspire how material aspects shape interaction (*theory contribution*, see Section 3.2 and the publication in Subsection 6.1.4) introducing **material terminology, the interaction material profile and the physicality representation spectrum**. The interaction material profile presents a novel structural approach to understand and dissect the different levels on which materials unfold as part of user interfaces, encompassing aspects on a micro and a macro level. It brings together material knowledge from different domains forming a unique model that could be interesting from many points of view (e.g., engineering, design, usage of user interfaces) and provides a number of departing points for future tools and methods (see future work section). The physicality representation spectrum as well takes a novel perspective by starting from a physical object or material and by consequently discussing different forms of digital and physical representations. It extends a quite established tradition in HCI, namely the application of metaphors taken from the physical domain to other types of representations, and allows a new view on this large design space. It is also well suited to serve as starting point for novel tools and methods in the future.
3. In six applications we explored **gestural interaction with mobile phones and interactive tabletops**, combining mid-air as well as touch surface-based gestural interactions (*artifact contribution*, see Subsection 4.1.1 and publications in Subsections 6.2.1 and 6.2.2). Based on these explorations, we derived an expert-based gesture set for mid-air gestures with mobile phones. Our lab-based study on the game “Poker Surface” furthermore revealed that for card based interactions, participants preferred the mobile-phone based mid-air gestures over touch interaction on the tabletop surface. This result shows that ready-available universal computational composite materials such as the mobile phone are well suited for interaction with playing cards in tabletop games if the applied metaphors by verb are convincing. Users preferred the tangible objects for interaction over pure touch interaction (physical over digital representation of playing cards). Moreover, from a designers perspective, this interaction is well suited to be applied to other application domains with private and public devices.
4. In a further case study we investigated **gestural interaction at the steering wheel** during driving in driving simulator setups (*empirical research contribution*, see Subsection 4.1.2 and the publication in Subsection 6.2.3). The contributions are twofold. First, we developed a steering wheel gesture set for 20 commands including music player, map and list interaction tasks based on a gesture elicitation study. Second, we conducted a lab-based experiment in which we compared a subset of the gestural interactions at the steering wheel to interaction with traditional middle console devices during driving and found a significant reduction in visual demand for the gestural interaction: gestural radio interaction caused 77.2% less glances and 67.1% less time spent looking at the interface. For gestural map interaction the number of glances were reduced by 58.1% and the time looking at the interface was reduced by 59.7%. Moreover, analyzing how materiality affected the interaction, we found two dominating aspects: the technical properties and affordances of the steering

wheel itself, and second, the metaphors taken from the material world that are applied in the gesture set itself. The gesture elicitation study revealed that, where applicable, transferring physical interactions directly or metaphorically to the digital domain is a preferred approach that also results in higher agreement among the users compared to gestures with abstract or symbolic nature.

5. To address end-user design of tangible user interfaces, we constructed an **end-user design toolkit** that realizes a novel approach regarding the separation of application logic and user interface and does not require wiring (*artifact contribution*, see Subsection 4.2.1 and publications in Subsections 6.3.1 and 6.3.2). The mapping of UI elements and interactions to dedicated functions is accomplished via fiducial arrangement and camera tracking. Our toolkit contributes to making, craft and DIY as HCI theme by taking a craft-based approach using classical craft materials combined with novel “maker-typical” technologies such as 3D-printing to create user interfaces. Furthermore, due to the toolkit design, which is very modular and allows easy extension, change or repair of single parts (be it UI elements or functional core parts) as well as the integration of all sorts of materials including recycled or biodegradable substances, the overall approach presents a novel contribution for the sustainability of personal interactive systems. In a design workshop, in which we asked participants to build one user interface for an alarm clock with the toolkit and one with paper prototyping, we found that the concept was overall understood and well applied. The provided “low-threshold” craft materials influenced the overall design task and supported the combination of paper and physical prototyping.
6. In a study **comparing a tangible and a digital tool for collaboration** in a tabletop game our results indicate that physicality of tools may enhance ownership and facilitate group awareness (*empirical research contribution*, see Section 4.2.2 and the publication in Subsection 6.3.3). We found significant differences regarding how groups of three players used the two versions. E.g., in the tangible condition initiating and resuming by the same person occurred significantly more than in the touch condition (77% vs. 56%). We also found better tool awareness in form of tool announcement in the tangible condition. These results contribute to the ongoing body of work that investigates tangible versus touch interaction in order to better understand how the interaction techniques affect the tasks. Moreover, the study presents a valuable example experiment how the physicality representation spectrum as presented in Subsection 3.2.3 could be systematically explored further. Both tools applied the meaning of the magnifier glass metaphorically. I.e., we applied metaphors by verb and noun to two different representations: a physical and a digital one and systematically compared these regarding effects on collaboration. Results like these should be collected and structured by the physicality representation spectrum with the goal of comprehensive design guidelines from a materials perspective.
7. With the **definition of the term “ephemeral user interface”** and the first fundamental analysis of this evolving class of user interfaces, including works from different art, research and practitioner communities, leading to a **design space for ephemeral user interfaces** this work provides an important and original contribution to human-computer interaction (*theory contribution*, see Subsection 4.3.1 and the publications in Subsections

6.4.1 and 6.4.2). First of all, this contribution is important in terms of focusing on materiality and user interfaces. The natural materials that are mostly used for interaction as part of ephemeral user interfaces generally provide diverse sensual interactions, provide rich aesthetics and expressiveness and allow for diverse forms of interactions. For example, we systematically explored solid, liquid and gaseous substances for interaction, each leading to unique typical forms of gestural interactions driven by the physical material. As the materials are so central in the design of ephemeral user interfaces, they also provide excellent examples to explore and understand the different aspects of the interaction material profile. Our discussion of ephemeral user interfaces systematically introduces many formerly unconventional materials to HCI. A second contribution lies in the investigation and discussion of ephemerality as a design concept as opposed to dominating strategies in computing and HCI.

8. We designed the **Soap Bubble Interface** to practically explore and investigate the concept of ephemeral user interfaces (*artifact and empirical research contributions*, see Subsection 4.3.2 and the publications in Subsections 6.4.3, 6.4.4, and 6.4.5). We built a fully working installation including a bubble generator that allows to generate bubbles in roughly controllable sizes and with or without fog inside, a liquid-filled bubble basin, a camera-based tracking system and an application with output facilities (projection, spotlights, and sound). Opposed to former interactive installations with soap bubbles, our interface explored the soap bubbles as input handles. By this we created a setup in which interaction styles and user behavior were strongly guided by the interface material used. In our observations of users engaging with the soap bubble interface in six public and semi-public settings we focused on material-based interaction constraints and material-driven user engagement, two novel concepts that yield potential to be further explored with other materials in the future. Our results revealed that the bubbles triggered diverse and rich interaction techniques among which were blowing, touching, and waving. Furthermore, we found a strong influence of the interaction material regarding cultural practices, physical conditions, the content and social practices. A second lab-based study, which compared the interface with real bubbles to a setup with plastic half-spheres as input for an interactive game, also revealed that users find diverse and creative interaction styles when interacting with the real bubbles. The users were very creative in trying out novel interaction techniques and in involving their whole body in order to gently move the bubbles. Moreover, although the game was harder to play with the soap bubbles, positive affect was rated significantly higher for the bubbles. So overall, with the soap bubble interface we conducted an in-depth exploration of soap bubbles for interaction and showed that they are well suited for playful, engaging and creative ways of interaction.

The prototype systems and the empirical work of this thesis reveal that material aspects matter for gestural, tangible and ephemeral interaction and that the canon of typical materials used for interaction should be widened and rethought. It is important that the materiality of user interface components get more attention in the design and development of interactions, and approaches such as the interaction material profile and the physicality representation spectrum provide use-

ful structural frameworks to understand how materials unfold and how they can be applied in different ways.

5.2. Future Work

In this work, I presented a materials perspective on human-computer interaction as an emerging research area. While we contributed to an emerging theory for this young field, practically explored dedicated aspects in case studies and set the foundations for ephemeral user interfaces, this thesis additionally opens up a quite large design space for future work. In the following, I will highlight some future long- and short-term topics along the structure of contributions applied to the included publications. I.e., I will start with open issues regarding foundations of a materials perspective on HCI and then cover future challenges and potentials for materiality and gestural, tangible and ephemeral user interfaces. Further trails for future work on the specific case studies can be found in the associated publications.

5.2.1. Foundations

To further develop a holistic materials perspective on HCI that takes inter- and transdisciplinary approaches into account, it would be beneficial to focus on three areas in future work: *material fabrication*, *material application* and *material appreciation*. These three themes were proposed by the designer Dennis Doordan as a simple framework to structure the perspectives that should be taken onto materials in product design (Doordan 2003). Applying Doordan's structure to human-computer interaction would mean to compile and generate knowledge around materials that is relevant for interaction and interfaces, which comes along with different requirements, questions and potentials.

First of all, HCI as discipline should develop a common knowledge about *material cultivation and fabrication* in order to really understand materials' properties and potentials. The most relevant and growing field here will likely be understanding and being capable of designing novel and smart materials with defined properties needed for certain interactions. This endeavor pre-requisites inter- and transdisciplinary approaches together with disciplines such as materials and chemical engineering. While some pioneering examples for such materials for interaction have been presented by HCI researchers, e.g. PyzoFlex (Rendl et al. 2012) as sensor material and bio-Logic as actuator material (Yao et al. 2015), material fabrication for interaction has yet not been systematically addressed as a field and knowledge domain beyond single explorations. Future work should provide common knowledge, databases and software tools from an HCI perspective to support designing novel materials for interaction. Ideally, these could start from a desired material profile based on the structure provided in this thesis and suggest potential solutions. Furthermore, material fabrication processes themselves also have been started to be addressed within the HCI community, e.g., by developing novel 3D-printing technologies to fabricate ma-

materials with desired properties for interaction (cf., Ou et al. 2016, Wang et al. 2016, Schmitz et al. 2015). In this area there is a need for future work that provides tools and toolkits to enable HCI practitioners and researchers to fabricate their own interaction materials more systematically.

Second, *material application* centers around how and which aspects of materials are used for interaction. In this area, HCI can learn from disciplines such as product design and architecture, which both have a long tradition in dedicating attention to material details and applying these in novel ways (see also Wiberg 2015). With the interaction material profile (Figure 3.2) I provided a structure to identify and reflect the different material aspects relevant for human-computer interaction. This structure can be used to analyze and inspire the use of materials in interaction. Future work could for example compile a catalogue of selected interaction materials including general material profiles as well as example application tools such as card-based design tools to support the application of materials within user interfaces more systematically. Overall, material application in interaction design still lacks comprehensive methods that support the process of finding suitable materials and appropriate mappings of the material properties within a user interface, which also needs to be addressed in the future. These could be inspired by approaches from product design (cf., Van Kesteren et al. 2007, Karana 2010, Sonneveld 2010, Karana et al. 2015), and should take into account findings from prior work (e.g., insights about how emotions and materials relate, how different shapes are experienced, see also Subsection 3.1.3). Additionally, further empirical studies are needed to understand how material properties unfold on the many levels addressed in the interaction material profile (e.g., for tangible user interfaces and data physicalization). A further novel perspective to the challenges of material application that does not only focus on physical materials but takes the full spectrum of interaction materials from digital to physical into account, originates from the physicality representation spectrum (Figure 3.3) presented in Section 3.2. Systematically exploring the design space framed by the physicality representation spectrum for specific materials presents a promising future work project that very likely will lead to novel insights regarding how physical materiality should be presented in user interfaces along the full physical-digital spectrum, an area that still remains with many open questions. This will even get more important in the future, as options for material representations will grow enormously. The physicality representation spectrum provides a novel approach to this as it starts from properties and meanings of physical objects and materials and makes design choices regarding their representation within user interfaces as well as related impacts explicitly.

Third, HCI as a discipline needs to concentrate more on understanding *material appreciation*. While material application focuses on designing with materials from a generative perspective this third strand takes an analytic view and could learn from disciplines such as material culture, anthropology, cultural sciences, and social sciences. Of course, this and the previous strand are intertwined in the sense that insights into material appreciation should be applied to support material application. While some research has been conducted in this area (cf., Subsection 3.1.8), these works still form a comparably small field, given that many aspects about how materials unfold within user interfaces as well as how digital artifacts impact users' lives are widely not understood. Future work could address this more systematically, e.g., by designing tools, techniques and methods how to get more insights about material appreciations, in short terms, but also after long terms of usage. Focusing on material appreciation with the interaction material profile in mind, it becomes clear that especially the macro level aspects, the material meanings,

the evoked emotions and the performative roles of materials are yet quite under-explored and still increasingly important in a society that gets more and more surrounded by digital artifacts (see also Giaccardi and Karana 2015). Standardized processes such as the human-centered design process as stated in DIN EN ISO 9241-210 as well do not reflect and integrate these aspects sufficiently. The process is rather reduced to user requirements. Especially long-term understandings about material appreciations of the final digital artifacts are not part of this process. Next to applying qualitative research methods in-situ such as ethnography, e.g., observations and interviews, future work could also focus on further tools and techniques to gather insights about material appreciations such as novel questionnaires focusing on macro level material aspects of digital artifacts. This trajectory could work on a material aesthetics of interaction design and be inspired by approaches such as the aesthetics of interaction (Lim et al. 2007) and the interaction vocabulary by Diefenbach et al. (2013) or by insights on materials and emotions (e.g., Davis et al. 2013).

The three strands *material fabrication*, *application* and *appreciation* serve as framework to structure the future research in this overall field and are applied here to highlight some example open issues. Generally, it would be valuable to establish the materials perspective on human-computer interaction as a field and to integrate it into the HCI curriculum.

5.2.2. Materiality and Gestural User Interfaces

Within the last decade, gestural interaction has evolved into a popular interaction technique within interactive systems. Consumer devices such as smart phones and tablet computers brought multi-touch interaction into everyday environments. Nonetheless, from a materials perspective, many aspects of gestural interaction with physical objects and surfaces – see also “tangible gesture interaction” (Van Den Hoven and Mazalek 2011) – are still to be explored. Based on the work of this thesis, I suggest three perspectives for future research on materiality and gestural user interfaces: first, *establishing gesture vocabularies for specific material classes*, second, *applying manipulative gestures with physical objects to human-computer interaction*, and third, *enriching surface gestures*.

Establishing gesture vocabularies for specific material classes: Exploring the design space for ephemeral user interfaces, we found a broad diversity of material classes, allowing for novel, expressive, multimodal and very diverse gestural interaction. Structured by different states of matters – solid, liquid, and gas – and further subdivided by perceived forms, we have started to collect and cluster typical gestures for specific materials as a starting point for establishing material-specific gesture vocabularies (Döring et al. 2013c) (e.g., gestural interaction with water). It could be valuable to integrate other evolving general taxonomy approaches about gestural interaction with objects into this approach, such as Angelini et al.’s tangible gesture interaction syntax based on *move*, *hold* and *touch* (Angelini et al. 2015a). In future, this space should be deeper and more systematically investigated by analyzing natural interaction with physical materials, by conducting studies that focus on the gestural design space with certain materials, and by building and exploring novel interactive systems with expressive materials. For these research

5. Conclusion

activities, adaptations of existing methods (e.g. the gesture-elicitation study approach (Wobbrock et al. 2009)) as well as novel methodical approaches that focus on materiality and gestures are needed (see also the “material-driven design” approach by Karana et al. (2015)). I believe that the materials perspective is especially suited to cluster material-related gestural vocabularies as well as to trigger richer interaction forms in the future. Resulting gesture vocabularies with material classes can also be transferred to gestural interaction with other material representations in interactive systems, an aspect that I address with the next perspective.

Applying manipulative gestures with physical objects to human-computer interaction: Manipulative gestures with physical objects are naturally part of human action, communication and meaning making. As I analyzed and demonstrated with the physicality representation spectrum (see Subsection 3.2.3), integrating real physical objects into human-computer interaction is only one approach that does not fit all applications and contexts. Thus, transferring qualities of physical materials and artifacts to other physical and digital representations remains a very central task for the design of interactive systems. With a focus on gestural interaction the challenges lie in transferring gestures from non-digital contexts to digital artifacts, which includes identifying, adapting and (re-)designing meaningful gestures for interactive systems. For example, using an off-the-shelf computational composite device such as a standard mobile phone as a representation for playing cards, as we did in the poker surface prototype (see Subsection 4.1.1), and designing meaningful mid-air gestures for the interaction, benefits from starting from gestural interaction with playing cards. As I argued before as part of the interaction material profile (see Subsection 3.2.2) and in the discussion of materiality and gestural user interfaces (see Subsection 4.1.3), aspects both on micro (e.g., form factors, technical integration) and macro levels (e.g., meanings and evoked emotions) need to be considered when designing the gestures (see also the discussion in (Angelini et al. 2015a)). This approach has the potentials to lead to richer, more diverse and more meaningful gestural interaction that is as well perceived as more “natural”. Starting from material qualities for manipulative gesture interaction has been explored exemplarily by Lee et al., who conducted a first gesture elicitation study with different deformable materials (Lee et al. 2010) or by Rendl et al., who designed a “Grip and Bend” gesture (Rendl et al. 2016). However, if we consequently adapt the materials perspective starting from manipulative gestures with physical objects to gesture elicitation studies, extending the method with a “priming phase” (discussed in Morris et al. 2014) could be valuable. In case of our poker surface prototype this would mean that a gesture elicitation study for finding gestures for the interactive system should be preceded by a priming phase with real playing cards.

Enriching surface gestures: Devices with surface gesture interaction are widespread nowadays. However, the diversity of touch interactions and the tactile stimuli they provide are quite limited, an aspect that has for example been addressed by Schiphorst before (Schiphorst 2009), who explored the richness of possible touch interactions. Coming from a materials perspective, we can open up the space for more diverse and more expressive touch surface gestures. This means future research needs to conduct further surface gesture studies and explorations of a broader variety of materials. An example study investigating gestures with elastic displays has been conducted by Troiano et al. (2014). Nevertheless, this research direction has yet only been preliminarily and exemplarily explored. Due to the invention of novel interactive materials that provide richer opportunities for gestural surface interaction, like Cillia (Ou et al. 2016) for example, which

presents an interactive hair structure that can be fabricated via 3D-printing, or the Jacquard project (Poupyrev et al. 2016) that offers a variety of different high-quality interactive fabrics at scale, it is very timely to address this design space for enriching surface gestures.

5.2.3. Materiality and Tangible User Interfaces

Within the research area of tangible user interfaces a focus on physical materials for interaction has always been important, as it is part of the concept to use real objects to present and manipulate data. Nevertheless, there are still many novel paths to explore and many very relevant aspects that are not understood by now. Based on the work of this thesis, I suggest three areas for future research on materiality and tangible user interfaces: first, *widening and understanding the material spectrum for interaction*, second, *personal fabrication toolkits for creating tangible user interfaces*, and third, *understanding the effects of different physicality representations*.

Widening and understanding the material spectrum for interaction: The richer and more diverse the properties of interaction materials are, the more opportunities and potentials arise for interaction designers to use these to represent and manipulate data as part of tangible user interfaces. Shape-changing interfaces (Rasmussen et al. 2012), for example, are a growing field of tangible user interfaces that explore novel material features. As stated in this thesis, there are many more materials to design and explore: e.g., the vision of radical atoms (Ishii et al. 2012) frames some of these highlighting programmable and smart materials, other interesting materials are more mundane but still quite unexplored as part of tangible user interfaces. Thus, future work should investigate materials from many perspectives in order to understand how they unfold on micro and macro levels as part of tangible user interfaces. Next to artifact contributions exploring materials the field needs further empirical contributions based on experimental studies that focus on dedicated aspects as covered in the interaction material profile.

Personal fabrication toolkits for creating tangible user interfaces: Facilitating the design of tangible user interfaces still is an important research aspect of the field. Especially in the context of personal fabrication and customization of products this also addresses non-expert users. Good toolkits yield, as we demonstrated with our end-user toolkit, the potentials to also address aspects of material diversity including the incorporation of everyday materials, modularization and sustainability. Recently, different approaches have been published to support the design of tangible user interfaces without wiring, for example using accelerometer modules (Hook et al. 2014) or force sensors (Hudin et al. 2016). The vision-tracking approach we proposed has a number of advances due to free material choice and shape that make it valuable to be further followed upon, assuming that future versions do not need fiducial tracking and allow simpler mapping mechanisms while still maintaining the craft approach (see also the camera-based tracking approach for 3D-printed interactive objects by Savage et al. 2013). Empirical research should address – both in short and long terms – how different users make use of the toolkits, what kind of materials they incorporate, what objects they design, how far personal devices are customized or recycled, or how the materials of the toolkit itself influence design decisions.

Understanding the effects of different physicality representations: Comparing different interaction styles regarding their suitability for certain tasks or environments has been an area of research within HCI for a while. Especially as the diversity of possible interaction styles is increasing due to technological advances, this design and problem space gets bigger. For the area of tangible user interfaces it is important to understand, where physical representations are better suited than digital representations. In our comparative study on physical and digital tool use we found differences and could demonstrate that it is valuable to investigate dedicated aspects. Even after 20 years research on tangible user interfaces there are many open issues in this design space. A better understanding of the effects of different physicality representations is needed. To proceed into this direction I provide the physicality representation spectrum as a structure to identify and name different physicality representations and suggest to apply these to specific research questions (e.g., as we did in our case study, to compare the representations regarding aspects of collaboration), which would result in a two dimensional grid to systematically explore potential future research. For example, based on recently found evidence that digital representations lead to lower-level construal whereas physical representations lead to higher-level construal (Kaufman and Flanagan 2016), it would be valuable to investigate different digital and tangible representations as part of user interfaces regarding their potential to support problem solving tasks.

5.2.4. Materiality and Ephemeral User Interfaces

Taking Ephemerality as a theme for user interfaces presents a novel and yet barely explored research trajectory. With our work on a definition for ephemeral user interfaces, the design space and the soap bubble interface as case study, we set foundations to term, structure and explore this field. We did this by exploring the field from a materials perspective: looking at ephemeral and natural materials as components of user interfaces. Nevertheless, keeping the physicality representation spectrum in mind, the integration of aspects of ephemerality into user interfaces opens a much larger space of design opportunities, also when more conventional interface materials are used. For future work, I see four main fields: first, *exploring application contexts for ephemeral user interfaces*, second, *tools and methods for designing and evaluating ephemeral user interfaces*, third, *ephemeral smart materials*, and fourth, *ephemerality as UI concept*.

Application contexts: While ephemeral user interfaces have been primarily explored in entertainment scenarios in the past (often as part of artistic installations), there are a number of further application contexts for which ephemeral user interfaces are well suited and that yield many yet unexplored potentials for future work. First, providing unobtrusive interactions in nature presents an excellent application field for ephemeral user interfaces. From a ubiquitous computing standpoint, which interweaves computing into all areas, it is desirable to explore unobtrusive ways to integrate technology into nature environments (see also Häkkinen et al. 2016). Examples for such environments could be hiking trails in parks or woods, fireplaces, graveyards, or beaches, for example. The natural materials as used in ephemeral user interfaces could fit well into these areas and provide many opportunities to incorporate the properties of the environment (e.g., temperature, wind, humidity, sun light) into the user interface and develop novel interactions (see also reflections on plants for interaction in Döring 2016b). Another interesting application area

is the home context, where to date digital artifacts often clutter up spaces and lack expressiveness as well as the development of meaningful personal traces of use (see also Odom et al. 2009). Ephemeral user interfaces that change over time and usually evoke a strong sensual experience and emotional response provide many novel design opportunities, both for user interfaces with short-term as well as long-term durability. Examples for applications could be, for instance, user interfaces on demand (see also (Walsh et al. 2014) for some thoughts into this direction), ambient communication devices, or ambient displays. The third application context is playful interactions in therapeutic environments where embodied interaction with sensually rich and engaging materials contributes to the sessions and the integration of digital tools provide additional value. This could be physical therapy, occupational therapy, or logopedia, for example. Within logopedia, exercises where patients have to blow in different intensities are quite common. Traditionally, engaging materials such as straws or soap bubbles are applied in therapeutic sessions. The soap bubble interface, for example, could provide a useful tool to engage diverse blowing techniques, e.g., as part of a playful application and at the same time allow automated personal settings and user documentation.

Tools and methods for designing and evaluating ephemeral user interfaces: As ephemeral user interfaces present a field for interaction design that comes along with novel opportunities and challenges, e.g., regarding interaction modalities with natural materials and dealing with ephemerality, novel tools and methods for designing and evaluating ephemeral user interfaces are needed. With our work, we have started to structure the aspects of material selection for ephemeral user interfaces. This process could be further supported by a catalogue of example materials and prototypes as well as their material aspects on micro- and macro levels, where the interaction material profile could provide a valuable starting point (see also Döring 2016a). Additionally, the design space for interaction modalities and techniques with ephemeral UIs starting from gas, liquid, and solid materials should be further explored and could be developed into a material-focused interaction taxonomy for ephemeral UIs (see also Döring et al. 2013c). An early research work that introduces a structured set of interaction techniques for fluids is given by (Wakita and Nakano 2012). Moreover, an important area of future work will be toolkits that support the integration of a variety of different materials for interaction. Here, some examples have been developed, e.g. Touché (Sato et al. 2012) and Makey Makey (Silver et al. 2012) that both use capacitive sensing technology to allow interaction with liquids and other natural materials. A further interesting question relates to formal modeling of ephemeral UIs that contain elements that change over time, sometimes due to complex environmental influences or due to their own rhythm. Last, even the evaluation of ephemeral user interfaces needs novel or adapted methods that take changing and disappearing UI elements into account.

Ephemeral smart materials: Thinking about all the qualities natural materials have and how they can be used for interaction, leads to the question, how we could design materials with exactly the properties we want for a user interface, e.g., ephemeral smart materials. Current activities in nano- and material sciences already focus on the invention of materials with novel features. In future, a typical UI design task might rather focus on the design and invention of a new material instead of selecting an existing one. Ephemeral natural materials could provide a valuable starting point to think about the features and possible interaction techniques future smart materials should provide from a user experience point of view. E.g., one focus could be on the aspects of ephemeral-

ality as introduced in our design space: how could we design an ephemeral smart material with a certain durability span, maybe computationally controlled? Could a material be reactivated, as e.g. already possible with ferrofluid sculptures (Kodama 2008)? What interaction techniques are possible for a certain set of novel materials? These open questions are related to current research programs like radical atoms (Ishii et al. 2012) or shape-changing interfaces (Rasmussen et al. 2012).

Ephemerality as UI concept: Analyzing the values that the integration of natural and ephemeral physical materials have for UI design can also help to improve the design of digital systems by applying ephemerality as UI concept. This is in line with the framework of reality-based interaction that suggests starting to think from real world phenomena when designing interaction. The designers' challenge lies in balancing computational power and reality. Taking the nature only as model and transfer insights back to other physical instantiations or the digital domain can be useful in some cases. Some examples for such nature-inspired UIs have already been designed – cf., robotic plants (Holstius et al. 2004), artificial flowers (Wallbaum et al. 2015), virtual ice windows (Häkkinen et al. 2013), or a soap bubble IPTV system (Bernhaupt et al. 2014) – but the potentials have not been fully utilized, neither has this design space systematically been explored. The physicality representation spectrum presents an excellent and novel structural approach to explore this space starting from the qualities natural material have for interaction and applying concepts of ephemerality to other hard- and software representations. Next to applying material qualities such as state of matter or texture, it can also support to explicitly focus on aspects of ephemerality such as transience, aesthetics, vagueness, or triviality. For instance, how could hard- and software elements grow, get older, degrade or even decay as things in nature do? In this sense, ephemerality could also be a strong concept for software design. In times where the quantity of stored data tremendously grows, where we have to process an increasing amount of information in nearly all environments of daily life, “forgetting” should be implemented as a feature (Bannon 2006, Mayer-Schönberger 2010). A popular application that applies default deletion to picture-based messaging is Snapchat¹. In a recent publication Xu et al. (2016) presented an analysis of snapchat uses, concluding that snapchat “only scratches the surface of how ephemerality might support users’ goals and interactions” (Xu et al. 2016, p. 1672). The authors presented a number of suggestions how ephemerality could be applied to interfaces vs. data, in different degrees, and to networks. This large space is to date mainly unexplored. Our approach of rethinking ephemerality in digital artifacts starting from ephemerality in nature presents a promising starting point to address these aspects on many levels.

5.3. Concluding Remarks

This thesis addresses many fundamental aspects of the emerging field of materiality and human-computer interaction. It provides a number of contributions, encompassing a survey of emerging material themes, material terminology, a material-focused framework for design and analysis, the design, construction and evaluation of working prototypes focusing on dedicated material aspects

¹ www.snapchat.com (last access: October 24th, 2016).

of interaction, and the foundation and exploration of the field of ephemeral user interfaces. I called this – admittedly quite broad – endeavor “a materials perspective on human-computer interaction”, highlighting that we as interaction designers win when we start from the material world and strengthen our focus on materiality in many regards. Furthermore, it addresses that it is timely to integrate knowledge about materials and materiality into our field, drawing on diverse disciplines such as material engineering, architecture, art, design, social sciences or anthropology. The current developments in ubiquitous computing and multisensory interaction design with an increasing interweaving of physical and digital worlds demand this. I hope that the achieved results and raised questions of this thesis will contribute to a materiality-aware and material-rich future of human-computer interaction.

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