PRE-PRINT

Weaving Fire into Form

Aspirations for Tangible and Embodied Interaction

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Ali Mazalek
Caroline Hummels

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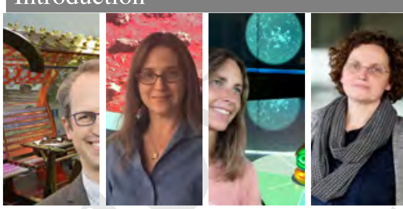

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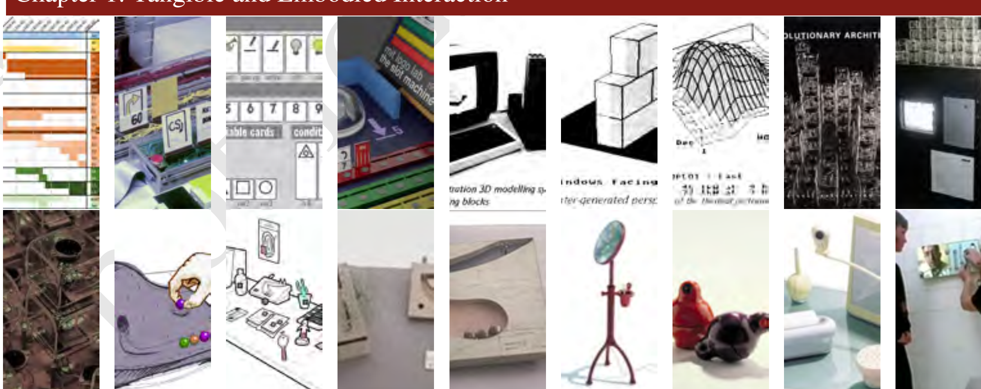

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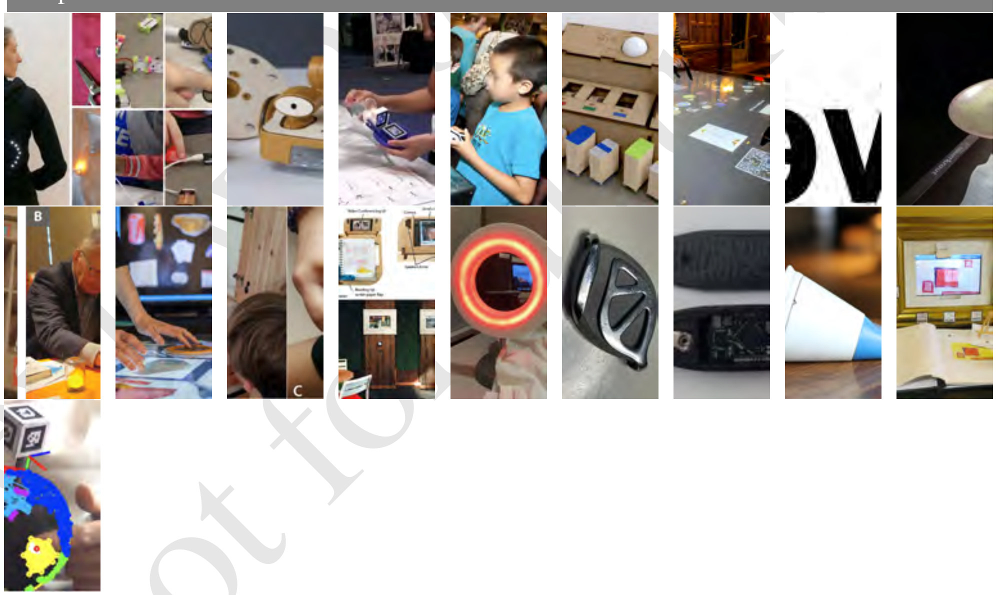

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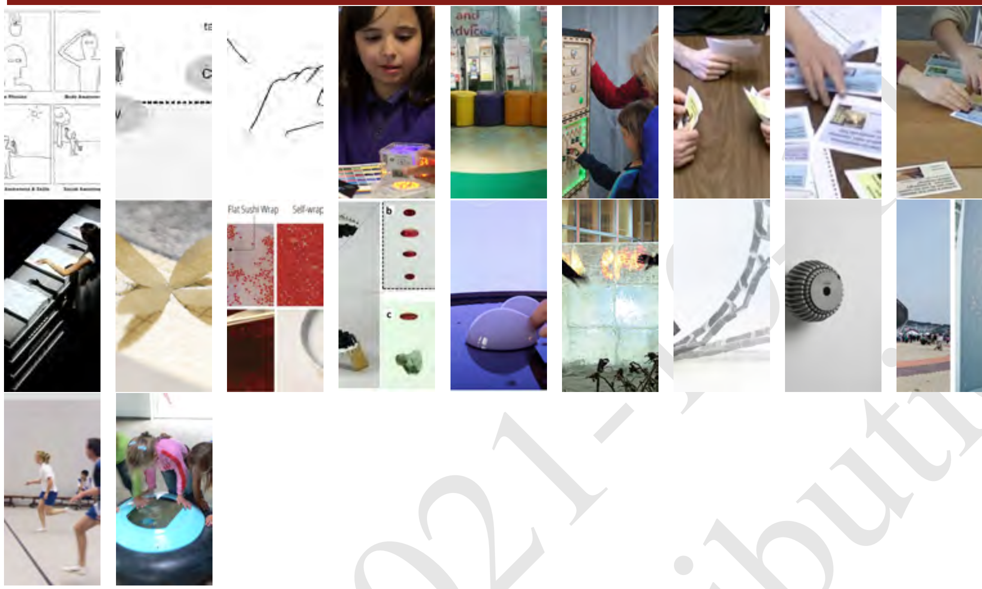

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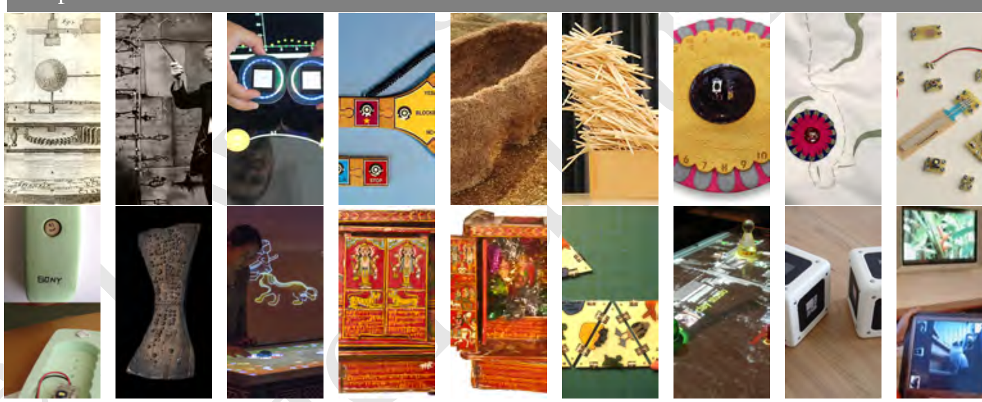

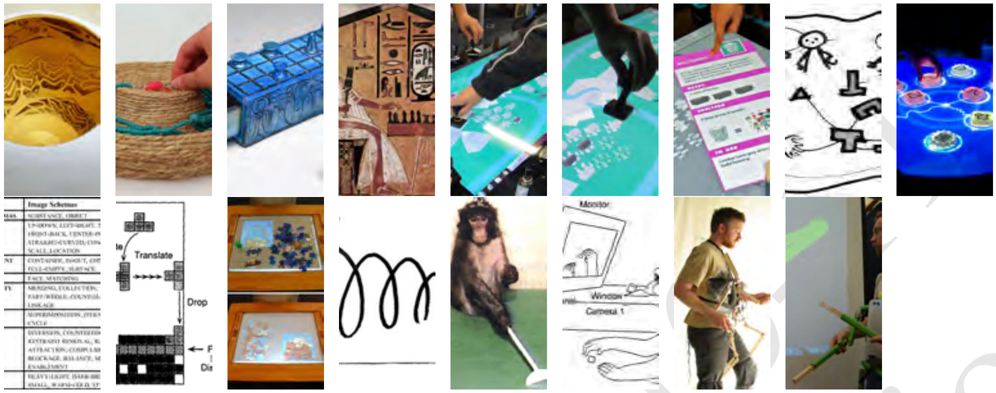

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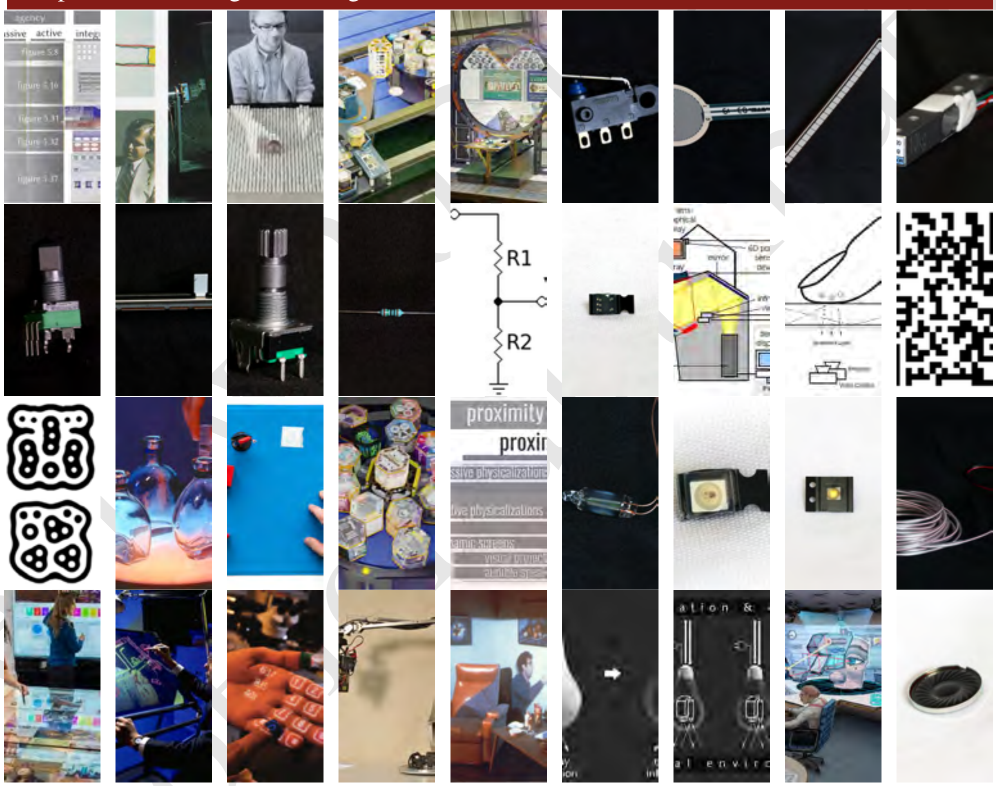

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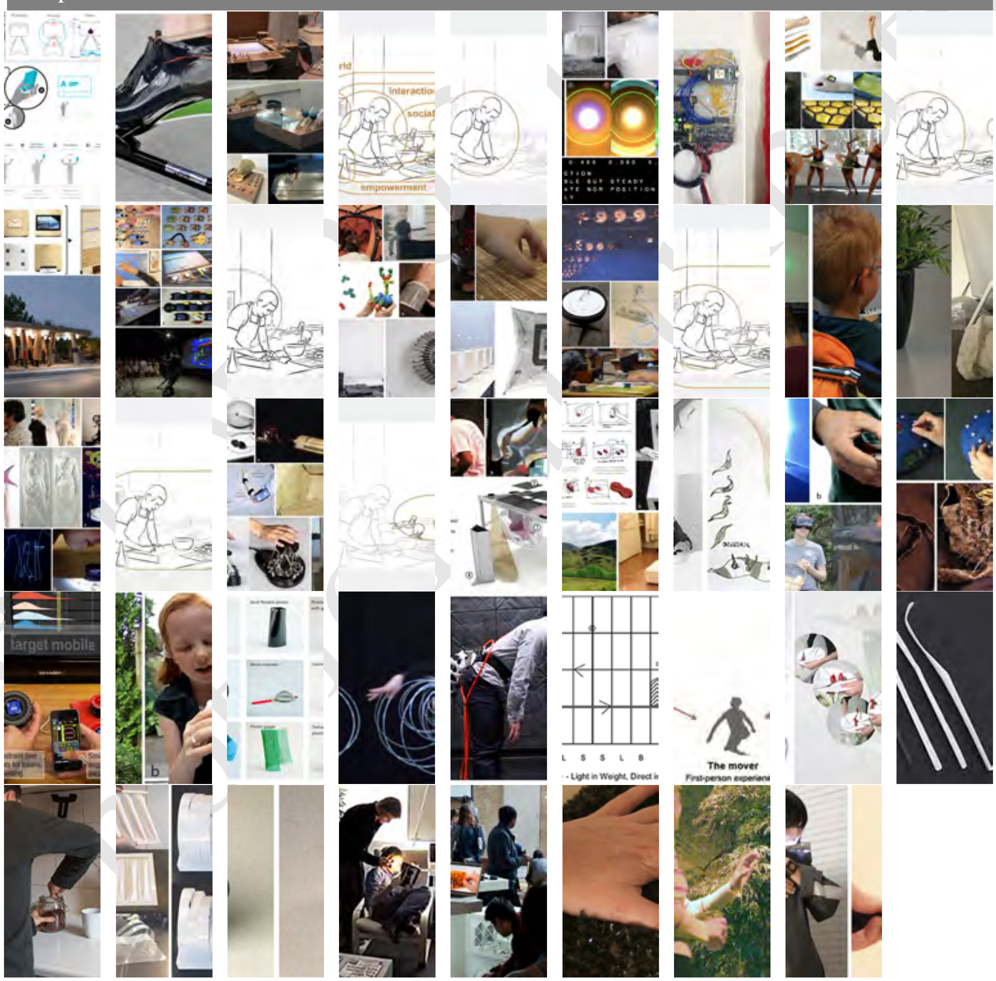

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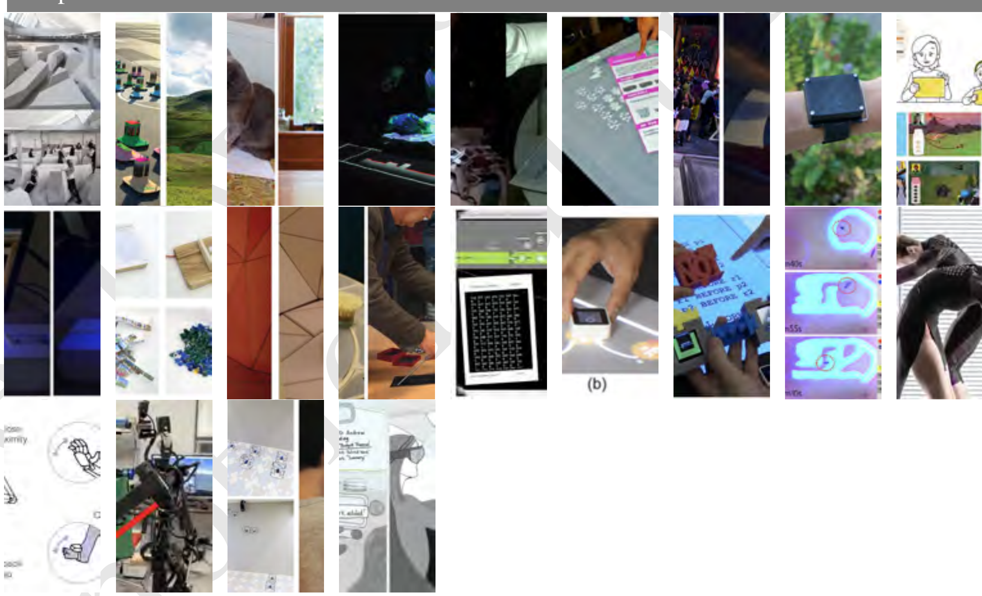

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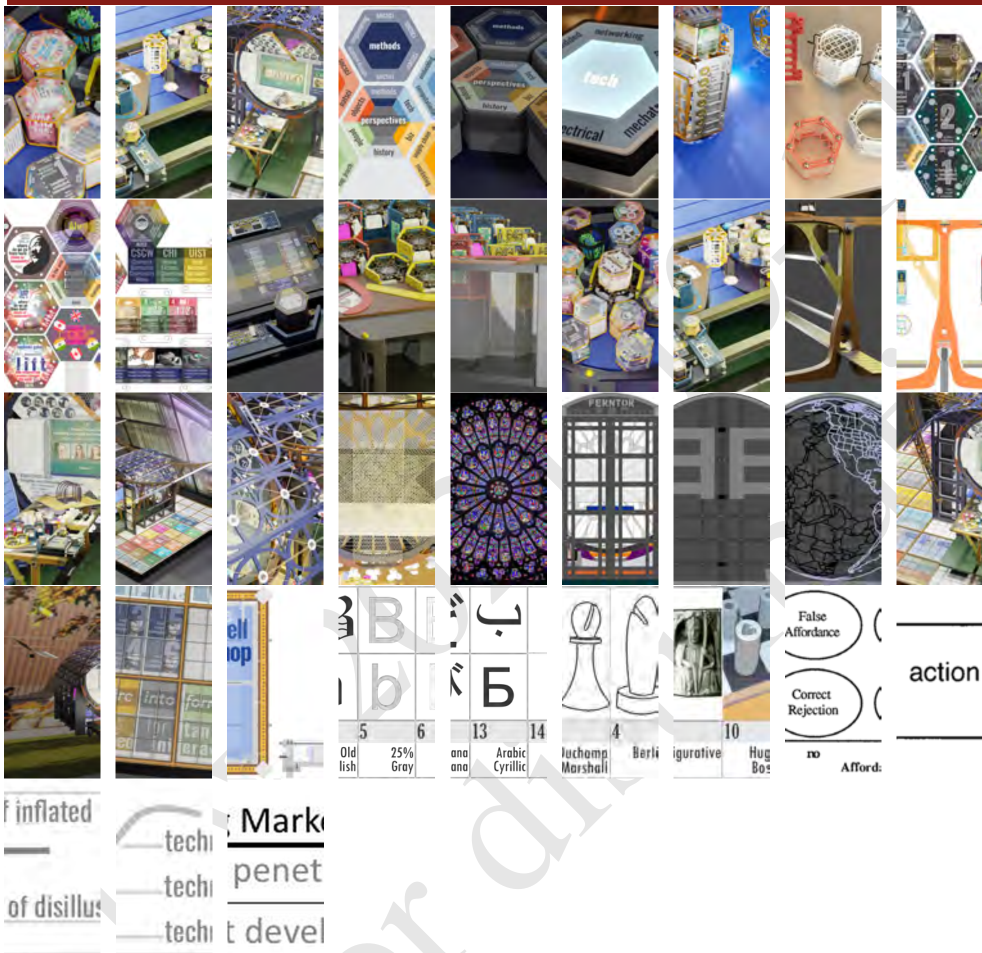
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FOREWORD

Prof. Hiroshi Ishii, *MIT Media Laboratory*

Abacus, the symbol of Tangible Bits. Photo Courtesy: AXIS

At the Seashore

> *"Where the sea meets the land, life has blossomed into a myriad of unique forms in the turbulence of water, sand, and wind. At another seashore between the land of atoms and the sea of bits, we are now facing the challenge of reconciling our dual citizenships in the physical and digital worlds.*
>
> *Our visual and auditory sense organs are steeped in the sea of digital information, but our bodies remain imprisoned in the physical world. Windows to the digital world are confined to flat, square screens and pixels, or "painted bits". Unfortunately, one cannot feel and confirm the virtual existence of this digital information through one's hands and body."* Hiroshi Ishii (1997)

In 1997, Dr. Brygg Ullmer and I presented the vision of Tangible Bits, and proposed the Tangible User Interface (TUI) that is based on the physical embodiment of digital information

& computation, in order to go beyond the current dominant paradigm of "Painted Bits" or Graphical User Interface (GUI) [Ishii and Ullmer 1997a]. Humans have evolved a heightened ability to sense and manipulate the physical world, yet the GUI based on intangible pixels takes little advantage of this capacity. The TUI builds upon our dexterity by embodying digital information in physical space. TUIs expand the affordances of physical objects, surfaces, and spaces so they can support direct engagement with the digital world.

Since the inception of "Tangible Bits," the world of "tangibles" has blossomed in the new field of HCI (Human-Computer Interaction) [Ishii 2008], bearing many fruits including the ACM TEI Conference (since 2007) and this historical book on TEI (2020) which you are now reading.

The ACM TEI Conference on Tangible, Embedded, and Embodied Interaction (TEI) started in 2007, organized by the pioneers of this field, Prof. Brygg Ullmer, Prof. Albrecht Schmidt, Prof. Eva Hornecker, Prof Caroline Hummles, Prof. Robert Jacob, and Prof. Elise van den Hoven. TEI succeeded in attracting a truly interdisciplinary audience including artists, designers, scientists, and engineers to discuss and create the future where the tangible physical world and virtual digital world are blended in harmony through the embodiment of computation and interactions in tangible form.

A variety of tangible applications are developed not only in the HCI academic community, but also in the IoT (Internet of Things) industry across the variety of fields, that include education, product design, fashion, health, communication, and marketing. TEI also made an impact on the media arts community, and we see a large number of tangible interactive arts in the SIGGRAPH and Ars Electronica, for example.

This book on TEI covers the foundation of Tangible User Interfaces (TUI) including the socio-historical origins of tangibles in human history, a conceptual framework of TUI, a variety of TUI applications, Cognitive and Philosophical Dimensions of TUI research, Enabling Technologies for TUI systems, and our aspiration for the future of tangibles.

As an introduction to the world of tangibles, let me share two stories of its origin, and the historical physical artifacts that inspired us to think about the future when "painted bits" (pixels confined on flat rectangular ubiquitous screens) will become "tangible bits" integrated into our everyday physical objects and environments. This leads to our friend and guru Dr. Mark Weiser's invisible computing vision [Weiser 1991a].

Origin - MIT Media Lab 1995

Our dream to "make digital tangible" goes back to 1995 at the MIT Media Lab where I joined in October as faculty, founded Tangible Media Group, and met Dr. Brygg Ullmer who became my 1st M.S. student. We worked together to create the post-GUI vision, co-authored the "Tangible Bits" paper [Ishii and Ullmer 1997a], and presented it at CHI 1997 in Atlanta together.

To survive at MIT, I was advised not to jump into the mainstream of the research field, but instead start a new stream on the edge. I wanted to contribute to the field of HCI by introducing new concepts, rather than making incremental contributions. The center of gravity within the field of HCI in 1995 was GUI (Graphical User Interfaces) – this is still true today. To develop something radically new, we tried to find the orthogonal vectors for each, and then identify a new space where those orthogonal vectors cross. It is like searching for an invisible blimp that appears only when multiple searchlights cross over it in the night sky. Luckily, we found the "tangible" blimp in the evening sky above Cambridge MA in the Spring of 1996.

GUI	**TUI**
Intangible, visual (eyes)	Tangible, tactile & kinesthetic (hands & body)
Remote control	Direct manipulation
Single-user, single hand	Multi-user, multi-hands
General purpose	Special purpose

Abacus

To explain the vision of Tangible Bits, I use the ancient computer we call an "abacus" as an important symbol to tell the story of tangible interactions including foreground & background interactions. When I was a baby, I was captivated by the abacus. It embodies the "digit" in a tangible form: beads that you can directly touch and feel. As a child, the abacus became a musical instrument, an imaginary toy train, and a back-scratcher because of its transparency and affordance, things that are missing in our current digital computers with a silicon black box inside. When my mom was busy with her bookkeeping, the music of the abacus let me know that I couldn't ask her to play with me. The abacus became the ambient media that made me aware of what my mom was doing in our small apartment in Tokyo.

Orrery

I visited the Collection of Historical Scientific Instruments at Harvard University in April 1996, and was struck by the beauty of the Orreries. An Orrery, one of my favorite tangible artifacts, represents our human knowledge of the solar system. I am deeply inspired by the aesthetics and rich affordances of historical scientific instruments, most of which have disappeared from schools and laboratories, and have been replaced with general-purpose pixels on screens. Through grasping and manipulation of these instruments through the handle, students who study astronomy can then be part of the solar system, and the movement of the planets around the sun is completely in sync with the senses of kinesthesia and proprioception. You can understand the lunar and solar eclipses through your body and haptic interactions with real physical objects. Alas, much of this richness has been lost to the rapid flood of pixels today.

Tangible Representation of Astronomical Knowledge: Grand Orrery in Putnam Gallery, Harvard University (photo by Sage Ross, CC-BY-SA 3.0)

Closing

I have to acknowledge and thank many visionary pioneers who shaped the digital landscape of today and built the new field of computation for humanity, including Dr. Douglas Engelbart, Dr. Ivan Sutherland, Dr. Mark Weiser, Dr. Alan Kay, and Prof. Bill Mitchell, who inspired all of us and encouraged me to embody my dream of tangibles in the past quarter-century with amazing colleagues in the TEI, HCI, and MIT Media Lab communities.

I also would like to express my sincere thanks to the next generation of leaders, and the co-authors of this book: Prof. Brygg Ullmer, Prof. Orit Shaer, Prof. Ali Mazalek, and Prof. Caroline Hummels, who are pushing the envelope of Tangible and Embodied Interactions (TEI) to the next level in order to make an impact on the way people interact with the digital world, access information, express themselves, and collaborate with people around the world by enjoying the richness of tangible and embodied interactions with our hands and bodies.

I sincerely hope you will enjoy reading this book not only to learn the history and the evolution of the tangible world, but also to feel the excitement of creating a new field, and envisioning the future of HCI or Human-Machine/Material Interactions.

I would like to close this foreword with my favorite quote from Prof. Malcolm McCullough's influential book "Abstracting Craft 1996" [McCullough 1996]:

> *Eyes are in charge, but hands are underemployed. By pointing, by pushing and pulling, by picking up tools, hands act as conduits through which we extend our will to the world. They serve also as conduits in the other direction: hands bring us knowledge of the world. Hands feel. They probe.*

Malcolm McCullough, Abstracting Craft 1996

REMARKS

March 16, 2021

On behalf of the ~100,000 members of the ACM, it gives me pleasure to follow ACM SIGCHI Lifetime Research Award recipient Prof. Hiroshi Ishii in adding introductory remarks.

As an ACM Book, "Weaving Fire into Form: Aspirations for Tangible and Embodied Interaction" joins a body of (presently) 34 ACM Books. A number of these concern Human-Centered Computing (HCC), under the highly valued leadership of HCC Editor Prof. Michel Beaudouin-Lafon, who was instrumental in inviting and shepherding this book. ACM Books is a critical initiative within and alongside our ACM Digital Library in promoting broader, deeper engagement with computing.

It is this broader participation in computing to which I will address my remaining remarks. I will begin with excerpts from the visionary works of $\mathscr{L}$ and $\mathscr{P}$. When first realizing these works, both were in their 20s. They shared a deep passion for computing, mathematics, music, and the particular style of "weaving" with which this book is concerned.

$\mathscr{L}$ wrote: "[My idea] contains two principal [kinds] of cards: first, operation cards; [and] secondly, variable / cards.… We … compose a series of cards according to the [action] required… …the [AE] might compose elaborate… pieces of music."

Independently, $\mathscr{P}$ also designed a system of cyberphysical operation, variable, and parameter cards, here used for expressive algorithmic design for controlling robotic systems – even by young children.

Ada $\mathscr{L}$ovelace, perhaps the world's first computer programmer, wrote of her tangible programming ideas in 1843 [Lovelace 1843]. ACM Fellow Radia $\mathscr{P}$erlman's system is the earliest functioning tangible interfaces using digital computing known to this book's authors [Perlman 1976a]; her "Slot Machine" is described in Chapter 1 of this book.

This female leadership in computing in general, and in the area of tangible and embodied interaction (TEI) in particular, has endured. All seven elected chairs of the ACM TEI Steering Committee – Eva Hornecker, Ali Mazalek, Elise van den Hoven, Saskia Bakker, Ellen Do, Ylva Fernaeus, and Audrey Girouard – are women. Three of the four co-authors of this book are women. At the ACM TEI 2021 (where I had the pleasure of delivering the welcome address), the Lasting Impact paper was co-authored by three women (Hannah Perner Wilson, Leah Buechley, and Mika Satomi).

As conference co-chair of ACM womENcourage 2016, and the third consecutive female ACM President, these observations deeply resonate with my optimism for computing more generally. And as detailed in this book, the momentum for broadening participation in computing (BPC) led by the ACM TEI community extends well beyond gender. At ACM TEI'21, the opening keynote by Dr. Stefanie Wuschitz described "feminist hackerspaces," including within economically-developing countries, highlighting both the broader skillsets, geographical span, and diverse potentials for economic development of TEI. The closing keynote, by Prof. Sile O'Modhrain, introduced technical, conceptual, and design innovations, while celebrating special TEI potentials in the performing arts, for visually impaired users, and beyond. And TEI21's organizing team, lead by my Austrian colleagues Prof. Martin Kaltenbrunner and Martin Murer, included 41 members from across Europe, Asia, Australasia, the Americas, Africa, and the Middle East, with an equally impressive diversity of disciplinary expertise.

In closing, the last year has been transformatively impacted by the COVID-19 pandemic. Through this, two central themes in humanity's response have been profoundly computational: the central role of telecooperation (engaged by my colleagues and I at JKU's Institute for Telecooperation); and the highly accelerated computational development of vaccines [Arnold 2020]. As highlighted in this book and its COVID-19 focused conclusion, TEI holds transformative potential both during and following pandemic times, across widely varying populations and circumstances, including for telecooperation, education, and biomedical applications. I commend you this book toward understanding and extending these land- and seascapes of bits and atoms. As we noted in ACM womENcourage 2016 ("Crossing Borders" [Anderst-Kotsis and Ayfer 2016]) with our headline quote of Rear Admiral Grace Hopper,

"A ship in port is safe, but that is not what ships are for. Sail out to sea and do new things."

Dr. Gabriele Kotsis is President of the Association for Computing Machinery (ACM). She is a Computer Science professor at Johannes Kepler University and an ACM Distinguished Member. She has organized ACM conferences and workshops, and in 2016 received an award in appreciation of her accomplishments regarding the ACM womENcourage conference series. Kotsis is a founding member of the ACM Europe Council, serving from 2008 to 2016. In 2014, she became an ACM Distinguished Member for her contributions to workload characterization for parallel and distributed systems, and for founding ACM Europe. Since 2016, she has been an elected Member-at-Large of the ACM Council.

INTRODUCTION

This is a story of atoms and bits. We explore the interweaving of "tangibles" and "intangibles," and especially of the physical and digital, toward understanding some of their wildly varying hybrid forms and behaviors. It is a story that is already many thousands of years old; yet also one that is very new, swiftly blossoming in growth and vitality.

For eons, our identities, habitats, and social interactions have been deeply rooted in physicality. Our bodies are physical; our world of things moveable and immoveable by our naked hands, also physical. Since the dawn of humanity we have also been creators and users of tools. Some of these are largely mechanical in nature – amplifying or transforming our abilities to lift or grasp. Others are seen as tools for thought – to help us remember, communicate, and compute. While we might view the hammer and the abacus primarily as tools of force or thought, respectively, they both engage our body and our mind. The choice of tool also has great implications for what can be expressed. As has been noted:

> "What you play with governs what you play, as you will soon discover if you try playing football with a shuttlecock or ping-pong with a puck." [Parlett 1990]

Further, our tools as well as the objects we create when using them are nuanced in their constitutions and expressiveness. As noted in this insightful characterization within Encyclopedia Britannia:

> "as with some other arts, the practice of architecture embraces both aesthetic and utilitarian ends that may be distinguished but not separated, and the relative weight given to each can vary widely from work to work." [Ackerman et al. 2000]

This assessment is broadly descriptive of design in general, and specifically of this book's topic: the nature, design, and use of tangible and embodied interfaces, and more broadly, tangible and embodied interaction (TEI). As noted in the architectural tension between aesthetics and utilitarian ends, TEI systems inextricably interweave computation, technology, and socio-physical context with aesthetics, design, and form, toward applications ranging from education and games, to science and the arts, and far beyond.

A related modern example can be seen in the successes of Apple Computer (at times the world's most highly-valued public traded company [Davies 2018]). While circuits, algorithms, and associated engineering are clearly critical facets underlying Apple's success, the masterful integration of these with world-class design – including physical, visual, and interaction design facets, expressing values such as quality, inspiration, and ease of use – has been equally central to Apple's attainments [Ullmer 2015].

But also critically, we see Apple's design approach of recent decades, aligned with Sony, Braun, Ulm, and Bauhaus philosophies from earlier decades [Cain], as neither stronger or weaker exemplars toward TEI's past and future than the profoundly different design perspectives of 1920s Art Deco, 1500s High Renaissance, 7th century Hōryū-jian (法隆寺), BCE 1500s Minoan, BCE3000 aboriginal design from countless cultures (most tragically extinct), and 2030 and 2330 genres of cyberphysical interaction devices deeply entangled with technologies yet to be conceived. This constellation also speaks to the relevance of physicist and philosopher Freeman Dyson's "clade and clone" concept:

> In biology, a clone is the opposite of a clade. A clade is a group of populations sharing a common origin but exhibiting genetic diversity so wide that they are barred from interbreeding. A clone is a single population in which all individuals are genetically identical. Clades are the stuff of which great leaps forward in evolution are made. Clones are evolutionary dead ends, slow to adapt and slow to evolve. . . .
>
> All this, too, has its analog in the domain of linguistics. A linguistic clone is a monoglot culture, a population with a single language sheltered from alien words and alien thoughts. Its linguistic inheritance, propagated asexually from generation to generation, tends to become gradually impoverished. . . . Linguistic rejuvenation requires the analog of sexual reproduction, the mixture of languages and cross-fertilization of vocabularies. . . . In human culture as in biology, a clone is a dead end, a clade is a promise of immortality.
>
> Are we to be a clade or a clone? This is perhaps the central problem in humanity's future. In other words, how are we to make our social institutions flexible enough to preserve our precious biological and cultural diversity? [Dyson 1979]

Synergistically, TEI draws great power from the evocative diversity of our physical world and social relationships. From a technology perspective, this is both distinguished from and complemented by the "black mirror" monoculture of contemporary multitouch devices. And from sociocultural and environmental perspectives, the potentials of TEI – both for good and ill – are profoundly amplified by the material and cultural diversity of our global cultural inheritance. This is not merely a gift; it is also an existential expectation, voiced in unison by our ancestors and our children's children.

In the words of Hiroshi Ishii, awarded the 2019 ACM SIGCHI Lifetime Research Award for his work on TEI [Liberty 2019]:

> Our goal is to invent new design media for artistic expression as well as for scientific analysis, taking advantage of the richness of human senses and skills we develop throughout our lifetime interacting with the physical world, as well as the computational reflection enabled by real-time sensing and digital feedback. [Ishii 2019]

On names, sister communities, and broader relevance

As evoked by Dyson's linguistic contemplation, names are powerful. This book's subtitle highlights our particular engagement with tangibles and embodiment, as terms we will unpack and engage at length.

But our arguments and precedents – and aspirationally, the relevance and audiences for this text – are interwoven with sister communities including ubiquitous and pervasive computing (ubicomp), augmented reality (AR), mixed reality (MR and XR), human-computer interaction (HCI), interaction design (ID), interactive product design (IPD), computational thinking, design thinking, STEAM (science, technology, engineering, arts, and mathematics), the Maker Movement, and the Colleges of Arts, Engineering, Computing, and Humanities (both metaphorically and literally). All these, and many more, are deeply interwoven with TEI, both in practice and future potential.

The book investigates and charts facets of TEI spanning the conceptual, philosophical, cognitive, design, and technical. We hope and aspire that both faculty, students, and the general public, toward highly diverse courses and projects, spanning these and other perspectives will find value in this book. When approached by students from differing backgrounds (in subject, seniority, and culture), we anticipate different audiences will prefer varying orderings and subsets of our chapters. For example, in some technology-oriented courses, we recommend jumping from chapter 1 to chapter 5, toward swiftly engaging project envisionment and implementation; then alternating between earlier and later chapters for broader and deeper conceptual background.

On aspirations

In November 1996, Paul Rand – known for creating the logos of IBM, NeXT, Westinghouse, and countless others, as well as his 1947/1970/2014 book "Thoughts on Design" [Rand 2014] – gave his last lecture at MIT. During the talk, host John Maeda asked if Rand viewed his work as art. Rand replied that his job, as a graphic designer, was to communicate; and whether any of his artifacts were to be regarded as art, left to the eye of the beholder [Maeda 2016]. This speaks to dual aspirations: to communicate, and (sometimes) to transcend the particularities of an originating context toward realizing broader impacts. We regard the same charge as broadly relevant to all TEI systems; and through this work, attempt to support these ends.

One further sister technology perspective is illustrative. In 1991, hypertext remained largely an academic curiosity. At the Hypertext 1991 conference, in a keynote address reflecting on decades of hypertext engagement, Frank Halasz noted "One of the main selling points of hypermedia [relates to] very large document collections [10K-100K documents]... Unfortunately, reality has yet to catch up to the vision" [Halasz 1991]. Meanwhile, in the conference's interactive session, Berners-Lee gave perhaps the first public demonstrations of his WorldWideWeb (WWW) browser. Years ago, estimates of total indexed and dark web pages ranged from 60 trillion to 100+ quadrillion [Christine 2016]. As noted in [Ullmer and Ishii 2000a], "Halasz's words bring a wondrous reminder of how quickly realities can change, and how profoundly long-latent visions can blossom.”

After engagement by more than 3,000 academic papers, and many more artistic, commercial, educational, and recreational entanglements, we see TEI swiftly evolving through such an inflection point. In resonance with these Web and Rand analogies, we see TEI and affiliated communities as aspiring to hybrid functional and aesthetic impacts; to supporting new paths for athleticism and entertainment, education and artistic expression; academic understanding and social inclusion; and toward other ends even more diverse than yesterday or tomorrow’s online Web. And in resonance with the deepening challenges and demands of our times, we aspire for TEI engagement with broader societal and sustainability challenges that will profoundly (re)shape our children and grandchildren’s futures.

If we, as a TEI community, will reach our envisioned futures and impacts remains a question. Meanwhile, this book charts both history and aspirations surrounding this relatively new discipline, and contemplates how we have and might realize culturally and materially sustainable futures. TEI systems consume material and energy; can they also reduce and transform material and energy consumption? Computational technologies have often sought to divorce themselves from physical reference to any particular culture; can TEI usher in ecologies of products deeply situated within niche physical and cultural traditions? We see such challenges as deeply important and worthy of engagement by many. In the coming pages, we examine many diverse trailblazing works, and provide wideranging conceptual and pragmatic tools and open-source exemplars, toward weaving the animating fires of computation and technology into evocative tangible forms, toward presence and action on many varied roads ahead. Through this book, we seek to celebrate and articulate the accomplishments of many others before and alongside us, and invite all to join this quest.

About the authors

Brygg Ullmer is a Professor and Chair of the Human-Centered Computing (HCC) Division within the School of Computing at Clemson University, where he also leads the Tangible Visualization group. His research interests include tangible interfaces, computational genomics (and more broadly, interactive computational STEAM), visualization, and rapid physical and electronic prototyping. He also has a strong interest in computationally-mediated art, craft, and design, rooted in the traditions and material expressions of specific regions and cultures. Ullmer hosted and co-chaired the inaugural ACM TEI 2007 conference; conference co-chair of TEI 2016; and is a steering committee member. Ullmer received M.S. and Ph.D. degrees from the MIT Media Laboratory, and a B.S. in computer engineering from the University of Illinois, Urbana-Champaign.

Orit Shaer is an Associate Professor of Computer Science at Wellesley College. She directs the Wellesley College Human-Computer Interaction (HCI) Lab. Her research focuses on novel human-computer interaction for the future of work and learning. Dr Shaer is a Senior Member of the Association of Computing Machinery (ACM), and a recipient of several NSF and industry awards including the prestigious NSF CAREER Award, Agilent Technologies Research Award, and Google App Engine Education Award. At Wellesley she was awarded the Pinanski Prize for Excellent Teaching. Dr Shaer is a steering committee member of the ACM conference on Tangible Embedded and Embodied Interaction (TEI) and served as a Program Chair in 2010, 2017, and most recently in 2020. Dr Shaer received M.S. and Ph.D. degrees from Tufts University in Computer Science.

Ali Mazalek is a Canada Research Chair in Digital Media and Innovation and an Associate Professor in the RTA School of Media at Ryerson University, where she directs the Synaesthetic Media Lab. Her research investigates how tangible and embodied media can support and enhance creative practices and processes, supporting new forms of expression and new ways of thinking and learning. She holds a cross-appointment at the University of Toronto's Faculty of Kinesiology and Physical Education, is an Affiliate Scientist at the Keenan Research Centre for Biomedical Science, St. Michael's Hospital, and is a member of the Ryerson Institute for Biomedical Engineering, Science and Technology (iBEST). She is a member of the inaugural cohort of the Royal Society of Canada's College of New Scholars, Artists and Scientists. Mazalek is a steering committee member of the ACM conference on Tangible, Embedded and Embodied Interaction (TEI), and served as a Chair from 2013-2016. She was a Program Chair for the TEI conference in 2008 and 2015. Mazalek received M.S. and Ph.D. degrees from the MIT Media Lab and a Hon.B.Sc. in computer science and mathematics from the University of Toronto.

Caroline Hummels is professor Design and Theory for Transformative Qualities at the department of Industrial Design at the Eindhoven University of Technology (TU/e). Her activities concentrate on designing and researching transforming practices with a focus on being-in-the-world theories, embodied interactions, technology-in-becoming, participatory sensemaking, aesthetics, and social resilience. Her recent quest aims at developing with her team a design-philosophy correspondence, in which philosophy informs design practice and design practice is used to philosophise, in order to tackle societal challenge through transformative practices. Caroline is founder and member of the steering committee of the Tangible Embedded, and Embodied Interaction (TEI) Conference, editorial board member of the International Journal of Design, and member of the Dutch Design Week sounding board. Moreover, she has given a large number of keynote speeches, invited lectures and workshops at conferences, international universities and for industry and governmental institutes worldwide.

Acknowledgements

We thank Prof. Hiroshi Ishii and Prof. Gabrielle Kotsis for their very kind introductory texts.

We appreciate the efforts and advocacy of our ACM Books HCC Editor, Prof. Michel Beaudouin-Lafon, for the invitation to write this book and invaluable encouragement and support throughout the journey; ACM co-editors Ashley Petrylak, Achi Dosanjh, and Diane Cerra, for their longstanding support and patience; to Barbara Ryan, for her highly valued facilitation; and to the book's reviewers, for invaluable feedback.

We give our warm thanks to the authors of Vignettes in this book; and to all of the members of the ACM TEI community, including the Steering Committee members for their years of advocacy and community support.

We give deepest thanks to our families, for their enormous patience and support throughout our journey with this book: to Miriam and Lilleken; Nitzan, Ben, and Daniel; Steven, Patrick, and Simon; Henny, Jonas, and Pepijn; and our parents.

We thank Clarissa Verish and Julia Burmeister for assisting with editing and production.

Our community has been greatly advanced by the participants in the ACM TEI conference series. While there are too many to individually name (e.g., in 2021, some 40 organizers and 350 participants), the host venues and conference + program chairs have been:

2007	Baton Rouge, US	B. Ullmer & A. Schmidt	E. Hornecker, C.C. Hummels, & R.J.K. Jacob
2008	Bonn, DE	A. Schmidt & H. Gellersen	E. v.d.Hoven & A. Mazalek
2009	Cambridge, UK	N. Villar & S. Izadi	M. Fraser & S. Benford
2010	Cambridge, US	H. Ishii, R.J.K. Jacob, P. Maes, M. Coelho, & J. Zigelbaum	T. Pederson, O. Shaer, & R. Wakkary
2011	Madeira, PT	M. Gross & N. Nunes	E.Y.L. Do, S. Brewster, & I. Oakley
2012	Kingston, CA	R. Vertegaal	A. Girouard, S. Jordà, & Y. Fernaeus
2013	Barcelona, ES	S. Jordà & N. Parés	M. Kaltenbrunner, D. Kirk, & P. Marshall
2014	Münich, DE	A. Butz & S. Greenberg	S. Bakker, L. Loke, & A. De Luca
2015	Stanford, US	B. Verplank & W. Ju	A. Antle, A. Mazalek, and F. Mueller
2016	Eindhoven, NL	C.C. Hummels, B. Ullmer, & S. Bakker	B. Hengeveld, D. Saakes, & L. Geurts
2017	Yokohama, JP	M. Inakage, H. Ishii, & E.Y.L. Do	J. Steimle, O. Shaer, & K. Kunze
2018	Stockholm, SE	Y. Fernaeus, D. McMillan, and M. Jonsson	A. Girouard & J. Tholander
2019	Tempe, US	S. Kuznetsov, D. Saakes, & R. Wakkary	L. Geurts, L. Hayes, & M. Lau
2020	Sydney, AU	E. v.d.Hoven & L. Loke	O. Shaer, J. v.Dijk, & A. Kun
2021	online × AT	M. Kaltenbrunner & M. Murer	K. Wolf & I. Oakley
2022	Seoul, KR		

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1 Tangible and Embodied Interaction

Computation, and especially its endowment with interactivity, has become one of the most transformative forces impacting human engagement with our world. Today, virtually every facet of human engagement has been touched, and often transformed, by the power of computation. While some computational systems remain "below the surface," without obvious indication of activity to lay observers, interactivity typically provides the face and hands of computation into the realm of human experience.

In the first decades of digital computation, both the input and output to computational systems was generally physical [Bush 1931; Ceruzzi 1981; Hartree 1946]. For example, with the 1940s ENIAC computer, data input and output was channeled via paper card or tape [Alt 1972], with programs and their parameters expressed through thousands of cables, sockets, knobs, and switches [Wilkes 1967]. Influenced by pioneering systems such as SAGE [Astrahan et al. 1957; Wikipedia d] and Sketchpad [Sutherland 1964; Sutherland et al. 1969], the input and especially output of computational systems has progressively shifted to virtual, screen-based forms.

This transformation has yielded user experiences that can be seen as visually rich but sensorily impoverished, engaging a very limited fragment of our human abilities to sense and engage our world. For example, consider the "presence" of a given computational application. From a few meters' distance, whether your friend is working on a laptop or tablet, smartphone or HMD – can you tell if she is balancing a spreadsheet, playing Solitaire, flying a drone, or hacking a genome? Are you sure?

Compare this with many of our most basic human engagements. In cultures where meeting a person is often accompanied by a handshake, the handshake carries many cues. The firmness of grasp, duration, perhaps moisture, and (in some contexts) perhaps a glove, all modulated with complex personal, social, and cultural chemistry, can express many things. Combined these with (e.g.) clothing, gaze, scent, and environmental ambience – how many of these modalities are fully engaged by your favorite "app?"

Where the embodied, performative act of a handshake is transitory, consider several physical artifacts from Africa, Europe, Asia, Australia, and the Americas that have endured for hundreds of years (Web companion 1.1). The Luba Lukasa provides tangible histories for nomadic African tribes, as accompanied and interpreted by oral narratives of people, places, things, relationships, and events [Chu and Mazalek 2019; Roberts and Roberts 2007; Ullmer

2002; Wikipedia 2018]. The Orrery provides a beautiful mechanism that both calculates and represents the celestial passage of planets. The Panama Canal control interface was used for nearly a century both to represent and control the state of the Canal's many functional elements. And the Japanese tea ceremony, with its physically performative rituals, environment, and equipment, while brought in existence in the 16th century [Kunkel 1999; Pitelka 2013; Wikipedia 2019], today still retains deep cultural and even technological significance.

Web companion 1.1 (ch1/figs/a1)

Luba Lukasa memory board *[Chu et al. 2015a; Roberts and Roberts 1996b; Ullmer 2012b]*; b) Orrery *Politikaner - Self-photographed, CC BY-SA 3.0, [Gould 1937]*; c) Panama Canal control interface. *Internet Archive Book Images from Carnegie Library of Pittsburgh:* [a]

[a] (flickr)

Tangible interfaces are hybrid physical and computational systems that awaken existing and novel physical artifacts with the mediating[1] power of computation. Tangible interfaces aim to engage the human senses, physical and cognitive capabilities, our cultural traditions and physical habitats, and beyond by interweaving the digital and physical worlds.

Embodied interaction unifies tangible interfaces with social computing, engaging concepts of embodiment from philosophy and psychology with the world of HCI. Embodied interaction stresses that products, objects, conversations, and actions unfold and are meaningful within our social and physical world [Dourish 2001b]. We perceive the world in terms of what we can do with it and how we can engage with it [Gibson 1979a]. By interaction with the world, we can access and express this meaning.

The study of Tangible and Embodied Interaction (TEI) spans philosophy, psychology, and theory; computing; electrical and mechanical engineering; making, design, art, culture; and well beyond. The creators of tangible interfaces include book binders, circuit benders, glass blowers, performing artists, weavers of code and fibers, and observers of humans in past, present, and future modes of engaging each other and our world.

Early examples

In an article titled "Why a diagram is (sometimes) worth ten thousand words" [Larkin and Simon 1987], Larkins and Simon note "[nothing] insures that an arbitrary diagram is worth 10,000 of any set of words." Similarly, "being tangible" in no way ensures that a given interface is "better" or even "as good as" a peer graphical, speech, or other interface. To the contrary, it is typically substantially more difficult to realize a "good" tangible interface than graphical

[1] The "mediate" term has long been used in technology contexts (e.g., computer-*mediated* communications, or CMC [Kiesler et al. 1984; Walther 1996]) where computers are not the focus of the interaction per se, but rather enablers and "mediators" through their sensing, display, processing, and online communications capacities

interface. When successful systems are achieved, they are most often products in equal measure of deep understanding, careful engineering, and inspired design.

That said, articulating the ingredients of "good design" is a complex and sometimes elusive activity [Hummels 2000b]. Toward an initial taste for the potential and diversity of tangible interfaces, we begin with providing an overview of exemplar systems.

We first consider several examples from previous millenia and the 20th century. We then consider some (relatively) more recent systems. For each, we combine pictures with text highlighting five key facets: concept, design, technology, philosophy+cognition, and aspirations. These facets will serve as entree and reference points for subsequent chapters dedicated to each of these themes. By "aspirations," we contemplate how each system might compellingly generalize toward use by broader audiences in the present and prospective futures.

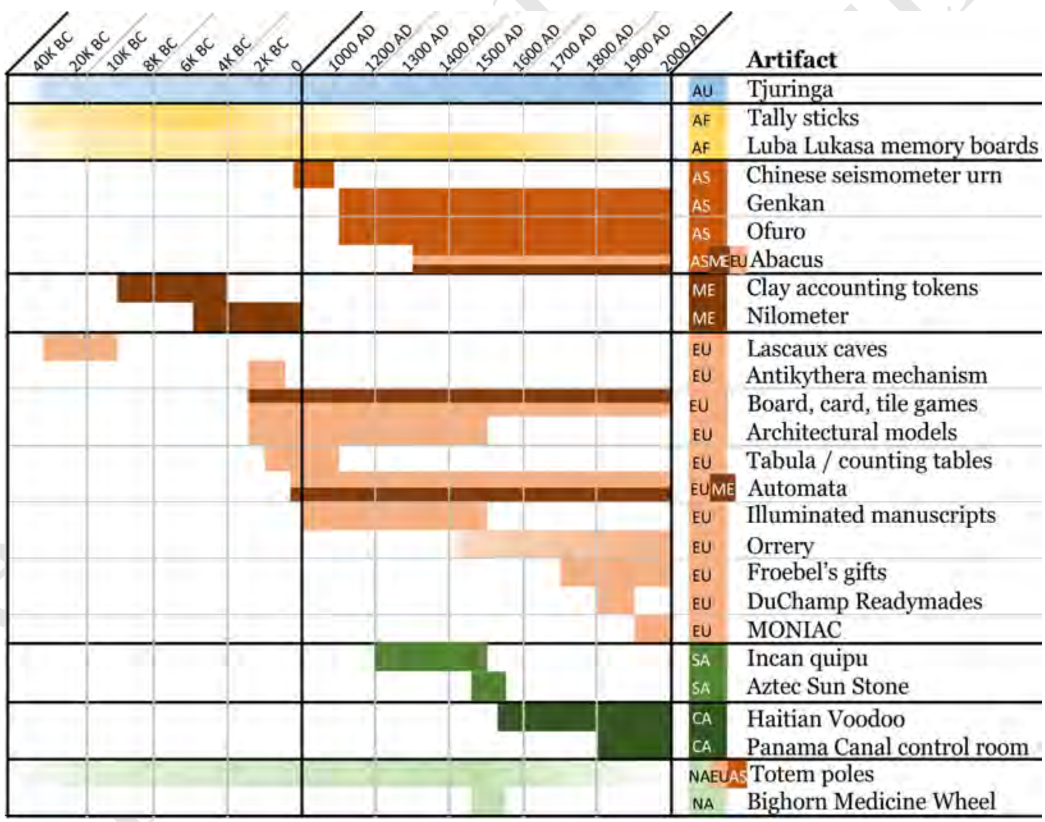

Figure 1.1 **Historical and cultural tangible precedents** Horizontal axis codes time, at varying granularity. Rows identify a range of illustrative historical TEI systems, in loosely chronological order (segmented by geographical region). Most of these are not specifically discussed in the book, but listed here both as historical vignette, and as a launching point for further study. Colors indicate different (sub)continents, confirming such uses span the globe.

Facilitating negotiations and collective memories: clay accounting tokens

As we have discussed in the context of Figure 1.1, humans of every culture have used physical artifacts in countless ways as tools for thought. Some of these are summarized in Figure 1.2. This is organized to express both the longevity of such practices, dating back at least tens of thousands of years; and the geographical and cultural diversity of such practices.

This is a tiny sampling of the great breadth of relevant examples. As indication, a small subset of such artifacts cast in the context of "physical visualizations"[2] contains hundreds of examples [wiki]. Beyond the history itself, we find many of these objects suggestive of future potential for computational mediation and use, in fashions celebrating their distinctive origins and cultural contexts.

As one of the older, best known, and (long ago) perhaps most widely used examples, clay accounting tokens were used in Mesopotamia for thousands of years (Figure 1.3) [Hockett 1960; Schmandt-Besserat 2007, 1996; Ullmer 2002].

Web companion 1.2 (ch1/figs/a2)

Clay accounting tokens (Wikimedia)

Concept: These physical tokens were used for bartering. Their discrete physical form facilitated both the negotiation process, and the keeping of records. In early generations, each token might represent a single cow or amphora (∼vat) of olive oil. In later iterations, tokens represented multiple cows, amphora, etc. After a bartered negotiation and agreement was complete, the tokens are thought to have been embedded within clay "envelopes" as formalizations of contracts. The tokens were frequently pressed on the exterior of the clay envelope to assist identification of their contents. (It is possible that the concept of "breaking a contract" may have literal origins in these clay contract-envelopes.)

Design: Over the roughly 5,000 year history in which clay accounting tokens are believed to have been used, their design evolved considerably. In earliest incarnations, tokens were simple geometric shapes (cones, spheres, disks, cylinders, and tetrahedrons). In later variations, they were inscribed with markings such as lines, dots, and circles [Schmandt-Besserat 2007; Ullmer 2002]. Some of these forms and inscriptions were representational; others, more abstract. Of these, Schmand-Besserat writes: "the conceptual leap was to endow each token shape... with a specific meaning. Consequently, unlike markings on tallies which had an infinite number of possible interpretations, each clay token was itself a distinct sign with a single, discrete, and unequivocal significance. While tallies were meaningless out of context, tokens could always be understood by anyone initiated into the system." [Schmandt-Besserat 2007] Some specific token design properties and conceptual features are summarized in Table 1.1

[2] "physical visualization," "data physicalization," and "tangible visualization" have been used as terms to describe the use of physical artifacts and the physical medium to visualize data of various forms. [Jansen et al. 2013, 2015a; Ullmer 2006; Ullmer et al. 2001; Vande Moere and Patel 2010]

Technology: From one perspective, the technology underlying clay accounting tokens was rudimentary and ad-hoc: clay could be scooped from the ground, and shaped appropriately by hand on demand. On the other, Schmandt-Besserat and others trace the progressive evolution of clay tokens and the tools surrounding their production and use to the origins of writing [Hockett 1960; Schmandt-Besserat 2007; Ullmer 2002]. This began with pressing the tokens into clay envelopes and tablets. In time, this evolved to stylus-based inscriptions upon tablets, then parchment, and onward to our present and future writing systems, along with many entangled technologies.

Philosophy and cognition: Clay tokens served not only as an accounting system, but also as a coordinated system for categorizing and communicating certain relationships within the world. They enabled "reference in absence," facilitating communication and negotiation about (e.g.) cows and olive oil without directly manipulating the entities themselves. This may also have held religious or spiritual significance: "The existence of such taboos [relating to literal representation] could explain, in fact, the earliest adoption of 'arbitrary' symbols or tokens... perhaps a compromise between the significance of the emblem and the insignificance of the pebble." [Harris 1986].

Aspirations: In their ~five thousand years of use, clay accounting tokens can be seen as an underlying medium enabling new forms of numeracy, commerce, and (through their evolution to written language) literacy. They can also be seen as engaging new audiences and introducing new forms of negotiative human interaction through their accessability and breadth of use. While their use faded some five thousand years ago, these accomplishments hold strong relevance and prospective parallelism to our present, and prospective futures. For example, with the rise in primacy of video and image on the Internet, as marked by channels including YouTube, Instagram, and Netflix, some write of "post-textual" futures [Kovač and van der Weel 2018; Manjoo 2018]. Especially amidst such trends, our attention is among our most limited human resources, rendering new mediums and mechanisms for engaging and helping us manage our attention – such as tangibles – correspondingly precious. Just as "post-textual" does not imply "non-textual," neither tangibles nor any medium are, across all contexts, "better" or absolute replacements for their alternatives. But the clay accounting tokens, and our coming examples, illustrate some of the moments, places, and contexts in which tangibles have and could hold compelling roles.

Expressing relationships and computational thinking toward broader audiences: the Slot Machine

Many precedents, practices, and potentials for TEI are interwoven with education. As one compelling example, the Slot Machine system (shown in Figures 1.3 and 1.2) allowed young children to program the behavior of robotic "turtles" [McNerney 2004; Perlman 1976a]. Lead by Radia Perlman [Wikipedia c] and Danny Hillis [Wikipedia a] in 1976 within MIT's LOGO Lab [Wikipedia b] under the mentorship of Prof. Seymour Papert [Wikipedia e], it allowed

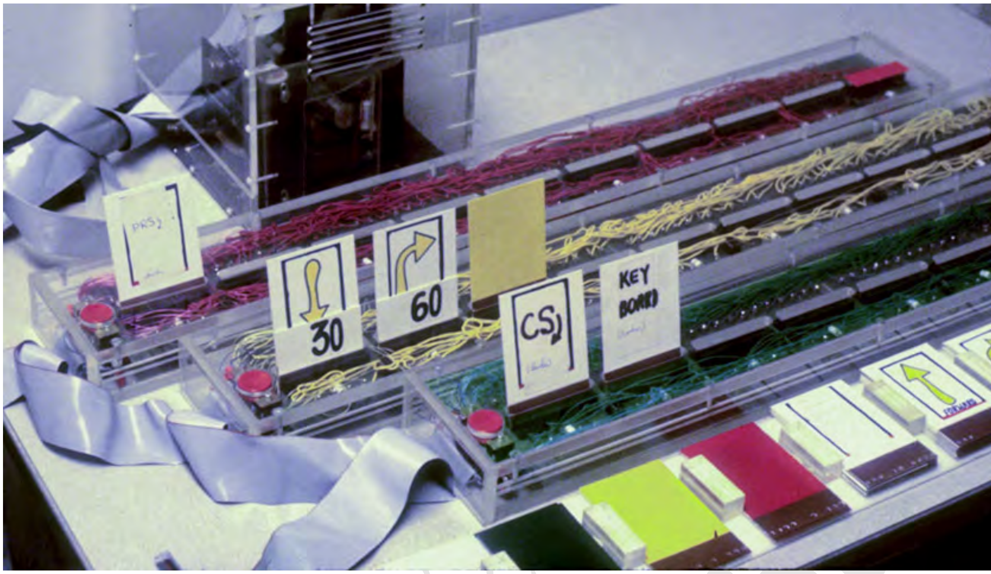

Figure 1.2 Slot machine *(Radia Perlman, MIT Logo Lab, 1976); photograph courtesy Robert Lawler and Radia Perlman [McNerney 2004; Perlman 1976a]*

expression both of simple robotic movements, as well as computational behaviors engaging more complex concepts (e.g., conditionals and recursions) that otherwise typically require a decade or more further cognitive development.

Concept: The Slot Machine was composed of labeled physical cards; colored physical slots, within which these cards could be inserted; and a robotic (and later, screen-based) "turtle." The turtle moved on the floor under control of a program tangibly expressed by cards, as sequenced consecutively within the slots. Three types of cards existed: action, number, and conditional cards. Each type had a different height, allowing several to be stacked in a given slot position while retaining physical accessibility and visual legibility. Three slots (colored red, green, and yellow) allowed individual card sequences to be composed; and also sister "subroutines" to be invoked. As examples, a forward-arrow "action" card stacked with a 4 "number" card expressed "move forward for four seconds;" while a turtle-against-wall "conditional" card stacked with a red "action" card expressed "run the *red* sequence of instructions when an obstacle is bumped." (Here, the "red card/sequence" referenced the cyberphysical card sequence composed within the red slot.)

Design: the slot machine makes a strong combination of visual representations (e.g., numbers, symbols, and diagrams labeling the cards) with physical representations (varying-height cards, slots, and the physical robot with its embodied movements).

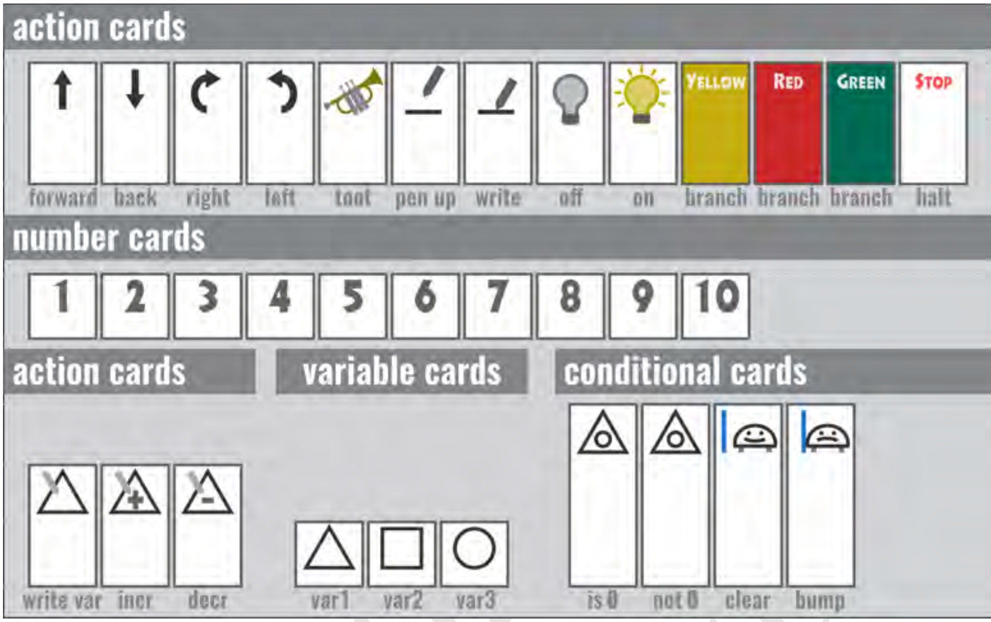

Figure 1.3 Slot machine: *cards illustrated in [Perlman 1976a], redrawn with fidelity to the originals. Action and number cards were implemented; variable and conditional cards were envisioned.*

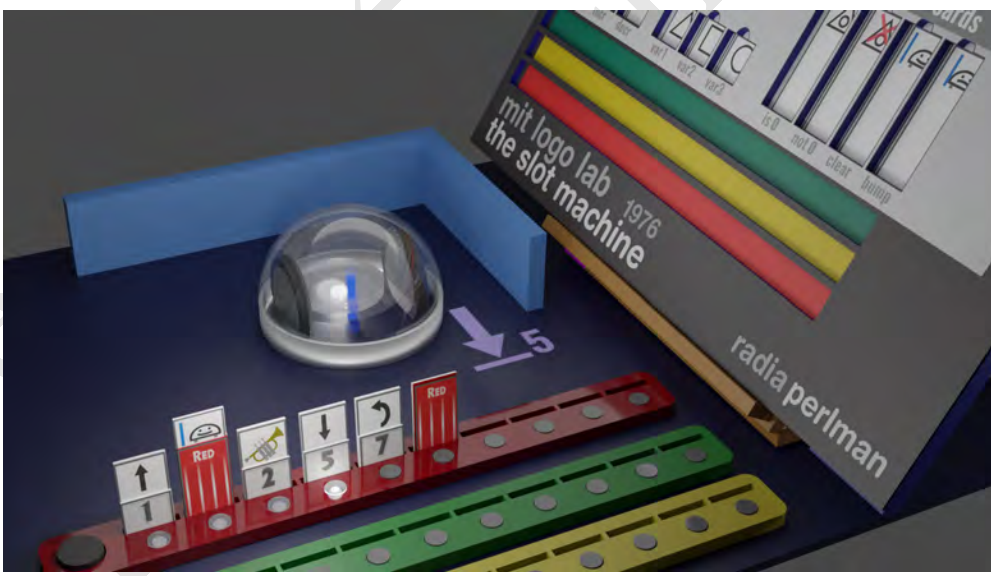

Figure 1.4 Slot machine *(Radia Perlman, MIT Logo Lab, 1976): "a Slot Machine program which has the turtle toot and walk in a different direction when it hits something" [Perlman 1976a]. 3D render of illustration from the 1976 manuscript.*

Technology: The slot machine sensed the slotted cards optically with a system of LEDs (likely infrared, and thus invisible to human eyes). Fabrication was with hand-cut transparent acrylic, with slot colors expressed by the insulation of the interconnecting wires. The slot machine was initially used to control mechatronic LOGO "turtle" robots. Later, they also controlled (or could have controlled) virtual screen-based turtles (potentially including large numbers of virtual or physical robots, as investigated within Resnick's StarLogo system [Resnick 1996]).

Philosophy and cognition: Many of the concepts children manipulated with the Slot Machine are known to be challenging to much older students. For example, an "investigation found... middle-school students were able to work successfully with several abstract constructs, but the students 'struggle with... conditionals... and recursion' [Werner et al. 2012]. This gives an indication that there might be a limit on the level of abstraction that students of this age can naturally work with, at least without a different pedagogical approach." [Duncan et al. 2014].

This resonates with Perlman's 1976 observation in the context of engaging children as young as four ine. Of this, Perlman wrote: "Another design issue is how easy the system should make it for the child to achieve interesting effects. If it is too hard, the child will become bored with doing rather mundane projects and will become discouraged if he tries anything harder.... With the Slot Machine, it is, if anything, too easy for the child to achieve spectacular results" [Perlman 1976a]. This speaks to implications of TEI-based pedagogical approach toward enabling and facilitating "computational thinking" [Wing 2006]. We elaborate on many specific cognitive aspects underlying the Slot Machine example, including external representations, Fröbel's gifts, and Piaget's cognitive theories within Chapter 3.

Aspirations: As perhaps the first tangible interface backed by digital computation, the Slot Machine in some respects anticipates and inspires most TEI activity, past and future. It remains a deeply provocative example of tangible tools for computationally facilitating child learning – a theme within which hundreds of systems have since been developed [Horn et al. 2012; Marshall 2007a; Price et al. 2003; Resnick et al. 1998]. The Slot Machine also illustrates prospects for tangible programming, not only for children but also broader audiences [McNerney 2004]. Both for tangible programming and more generally, it provides prescient precedent toward not attempting physical embodiment of *all* possible commands and data, but rather of the "key objects of interest" [Hornecker and Buur 2006a; Ullmer 2002; Ullmer et al. 2005a].

Putting things together: the Building Block System and Universal Constructor

Beginning in the late 1970s, UK researchers Robert Aish, John Frazer, and their colleagues independently lead the design of many tangible interfaces supporting modular interfaces for engaging the architecture of buildings [Aish 1979; Aish and Noakes 1984a; Frazer 1995; Frazer et al. 1980a]. Two inspired examples of their work from this period are the Building

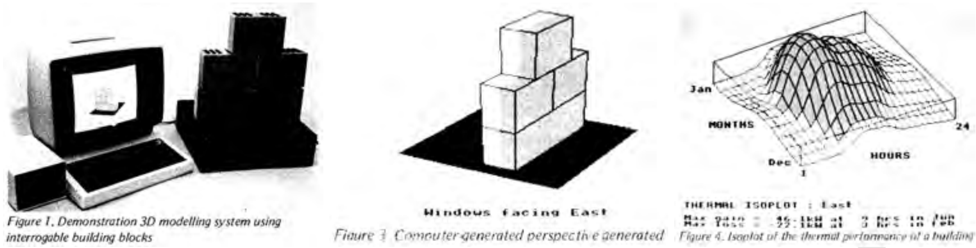

Figure 1.5 Building Block System *(Robert Aish, Ove Arup, 1984): [Aish 1979; Aish and Noakes 1984a] (courtesy Robert Aish).*

Block System (BBS) [Aish and Noakes 1984a] (see Figure 1.5) and Universal Constructor [Frazer et al. 1980a] (shown in Figure 1.6).

Concept: Both the BBS and Universal Constructor centered around modular systems of instrumented physical blocks. The configuration and manipulation of these blocks could be sensed and mediated by several forms of computational systems. For BBS, this mediation often took place via text and graphics on a proximal computer screen. With Universal Constructor, this display was often via constellations of LEDs within each of dozens (sometimes hundreds) of physical cubes. With BBS, one particularly notable example application related to energy consumption. As architects or their clients reconnected BBS blocks to shape a prospective building of varying spatial profile (e.g., taller vs. wider realizations of a given floorspace), the projected energy consumption across time of day and time of year were visualized on the screen. For Universal Constructor, one example "content" was cellular automata "contained" within each cube, representing (e.g.) prospective movements of human habitants within the structure.

Design: For BBS, each module took the form of an oversized, opaque LEGO™-like block. These could be mechanically interconnected, much as their smaller LEGO™ kin; with the structure sensed by integrated electronics. The screen-based mediation can be regarded as a kind of "magic mirror" [Grosjean and Coquillart 1999; Looser et al. 2004], "reflecting" back the physical structure, interwoven with augmentations from the associated simulations.

With the Universal Constructor, with working prototypes realized in 1979 and 1980, physical cubes were used as the constructive element. Here, the cubes' transparent walls exposed their LED, microprocessor, and supporting electromechanical enablers. This could be regarded as complementing the complex dance of their lit cellular automata behavior with the evocative complexity of their underlying implementation.

Technology: For sensing the configuration of blocks within the BBS, Aish describes a tree-based scanning system by which complex, many-layered block combinations could be be interrogated using serial communication protocols. He describes plans to reduce these electronics to a single custom VLSI CMOS chip. (It is unclear how microcontrollers or microprocessors were used in practice.) For the Universal Constructor, in the 1979-80 two-

Figure 1.6 Universal Constructor *(by John Frazer; iterations upon working prototypes dating to 1979): [Frazer 1995; Frazer et al. 1980a] (courtesy John Frazer).*

dimensional version, hand-breadboarded modules with pluggable interconnects, as physical proxies for self-replicating cellular automata, were realized [fra 1981; Frazer et al. 1980a]. In a 1993 version with Tomas Quijano and Manit Rastogi, the system was globally initialized and synchronized by a strobe flash, with each autonomous cell communicating via infrared with neighboring cells [Frazer 1995].

Cognition: Aish focused on implications of his work for facilitating collaboration, especially between experts and broader populations. "It is suggested that the most important potential contribution... will be to enhance the relationship between the client and the design team.... It will be possible for the architect to directly demonstrate to clients... modifying the model of the proposed building and presenting the resultant changes in the predicted costs and performance" [Aish 1979].[3] This is resonant with theories of distributed cognition, an approach which "explores how cognitive activity is distributed across internal human minds, external cognitive artifacts, and groups of people, and across space and time" [Zhang 1997]. Distributed cognition and "cognition in the wild" [Hutchins 1996] will be elaborated in Chapter 3.

Aspirations: Aish, Frazer, and their collaborators pioneered at least two major themes: (building) architectural applications (often engaged and published within professional contexts of that discipline); and constructive representations of cyberphysical content. In a later variation, illustrating some of the potentials of the cubes of Heaton [Heaton 2000] were discussed as including virtual worlds and social media implications. Here, each cube might "contain" (handles to) ten, ten thousand, or ten million people, and their derivative activity: tweets, posts, etc. The glowing, transforming shadows, etc. of these tangibles in response to movement and activity of their virtual contents; or the manipulation of the tangibles, hold powerful present and future (e.g.) social media and broader implications.

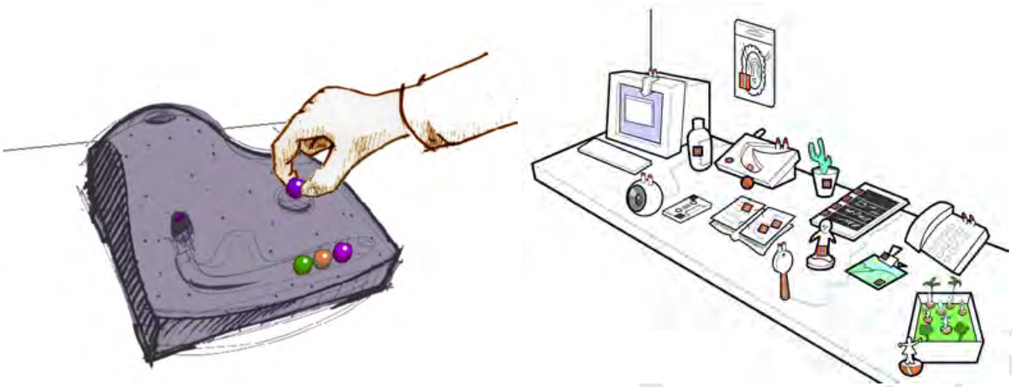

Figure 1.7 Marble answering machine *(Durrell Bishop, RCA CRD, 1992): a) Illustrated still from original animation [Bishop 1992]; b) Illustrated still from product ecologies envisionment. (courtesy Durrell Bishop)*

Objects as containers of voices, identities, ++: the Marble Answering Machine

At the Royal College of Art (London) Computer-Related Design program in the early 1990s, one of Gillian Crampton-Smith's introductory several-week projects challenged students to design a telephone answering machine. Then-student Durrell Bishop's response, an animated (and later, working prototype) envisionment of the "Marble Answering Machine" (shown in Figures 1.7 and 1.8) is widely regarded as an inspiration to many in the tangible interaction field – and more broadly, as an example of outstanding interaction design. E.g., in the book *Interaction Design: Beyond Human-Computer Interaction*, Bishop's vision is celebrated in the first figure as a paradigmatic example [Preece et al. 2015].

[3] An expanded version of this text is revisited and reinterpreted in Konkel, Ullmer, Shaer, and Mazalek, ACM Personal and Ubiquitous Computing 2020 (forthcoming).

Durrell Bishop, Co-Founder of Line-us

I am a product designer so my job is to communicate the role and purpose of man-made products. It is also to make sure they work, sell and can be made.

In the early 1980s, I was introduced by my friend and fellow student Chris Murray to the work and ideas of young postmodern product designers grappling with the question ‘how should a physical product represent its purpose?’ I realised then that chips were replacing mechanics – in the process, breaking the foundations of formal design. A product’s form, which makes it recognisable, was no longer being derived from the relationship between its mechanical elements and its use. I went back to college in the early 1990s to explore the question, ‘how do we actually read our environment through objects? – which leads to ‘how do the objects represent their role in new man-made systems?’ This work from the early 1990s relates closely to the origins of Tangible and Embedded Computing: how we use the properties of physical objects to represent and manipulate new systems.

We are all brought up to move fluidly through the world, subconsciously reading our environment and the physical representations of our society, yet we don’t tend to use this tacit physical knowledge when we create the computational representations of social systems, apps or sites. The tendency is to sum up a group of ideas into an icon and legend for a button. The icon is a fixed symbol for an idea and the button just invitation to carry out the idea. A physical tool, like a ruler, is far more complex than a button labeled measure – it describes the idea of a unit of length and its form lets you compare this against other physical objects. Our understanding of the ruler’s properties also allows us to manipulate it in countless numbers of ways. Tangible Computing takes this further and places actions within a physical context. For example, a digitally augmented ruler might be placed between two ideas on a map to measure their relationship.

I believe we have a problem in design: we are great at adding new associations and metaphors to create desire in our new products, but have not worked out how to graphically or physically represent the non-mechanical ideas – the underlying parts that we need to see that build the foundations of descriptions for new products. Instead, we resort to buttons (icon and text) which usually are metaphors to earlier tools. This approach has divided our society between users of icon/text based interfaces and text-based programming that builds them. Code is a description of behaviour; code describes a system and its potential possible actions. A physical engine or the layout of café are also descriptions of the behaviour of a system and the potential actions within it. Yet the abundance of people that can use their experience of life and the physical world to work out how to run and design a successful cafe or mend an engine are unlikely to also be text-based programmers. Of course, a programmer can work alongside a café owner to produce the app to help café layout, or help diagnose a fault in an engine. But this does not make the most of people in our society. By not using the memorable and descriptive principals of the physical world, we take away the ability of those with the experience to create the new tools. It is the self-descriptive nature of well-designed tangible and graphical objects, combined with mans' ability to read their purpose that will open new opportunities for our society to understand and manipulate the computational systems we are building.

Durrell Bishop is a product and interaction designer. He received his master's in interaction design from the Royal College of Art in London, where he stayed on to do research before joining Interval Research in California. He then pursued game design with Dancing Dog and co-founded "Itch" before joining IDEO as a senior interaction designer in London. He left IDEO to develop interactive media and products, and is one of the pioneers of internet-connected devices. He has taught product and interaction design at RCA for over 20 years. Most recently, he's developed Line-us, a robotic drawing arm connected to the internet.

Concept: A number of physical/tangible elements are present within the answering machine envisionment, each with corresponding computational associations and mediations:

- *marbles:* physical marbles acted as physical *containers* and *embodiments* of voice messages. Subsequent mechanical and human actions upon these marbles allow them to simultaneously serve as both *representations* and *controls*.
- *answering machine:* The machine itself provides a number of loci for facilitating human interaction with marble-messages. The marble-"expeller" embodied a visual, auditory, and haptic indicator for the arrival of new messages. The marble holding area passively indicates how many messages have been received, while exposing each marble-message toward subsequent interaction. The machine's access touchpoint (visible in Figure 1.7a below the hand) provides a locus through which marble-messages can be retrieved. Finally, the recycle chute allows marble-messages to be returned for further use when no longer needed.
- *ecology of passive synergistic artifacts:* Bishop's animation portrays an open-ended system of passive artifacts which can be combined with marble-messages. Several dishes were illustrated as sorting and holding areas for different household members. A marble rack might allow longer-term storage, with marbles serving as passive reminders of pending opportunities. The marbles also might also meaningfully and pragmatically pass through pockets, jars, and a wide spectrum of purpose-designed and ad-hoc worldly habitats.
- *ecology of active devices:* Bishop also illustrates how ecologies of active devices might interact with marble-messages. When placed within the access constraint of a supporting

Figure 1.8 Marble answering machine *(Durrell Bishop, RCA CRD, 1992): a) System of physical products prototyping object ecologies; b) Closeup of physical marble answering machine prototype. (courtesy Durrell Bishop)*

telephone, a call is initiated to the marble's virtual point of origin. An access-constraint on a computer might allow screen-based message retrieval or storage (illustrated later with mediaBlock monitor slots[Ullmer et al. 1998]). As illustrated in Figures 1.7b and 1.8a, Bishop was adamant that this potential ecology of interoperating devices was at least as interesting to him as the answering machine itself.

Technology: The messages might be stored in the marbles, the machine, or elsewhere (e.g., online "in the cloud"). The envisionment can be seen as agnostic, and the illustrated behavior need not, in general, superficially depend upon the implementation. That said, "in general" is not always so; implementational details matter, sometimes with profound implications [Hicks 2013; Nieva 2018]. The envisionment illustrates marbles of several different colors, leaving open-ended whether these colors are random or purposely assigned; and whether the colors are passive, or actively changeable (e.g., through embedded LEDs, bistable e-ink, etc.).

Philosophy and cognition: Cognitive scientists have approached a growing consensus that the process of cognition lies not only in the human mind, but also within the physical world. Both the marbles, and the ensemble of active devices (e.g., answering machine and telephone) and passive (dishes, racks) serve, from a cognitive science perspective, as *external representations*. These are "knowledge and structure in the environment, as physical symbols, objects, or dimensions, and as external rules, constraints, or relations embedded in physical configurations" [Zhang and Norman 1994]. "External representations are neither mere inputs and stimuli to nor mere memory aids to the internal mind. They are intrinsic components of many cognitive tasks; they guide, constrain, and even determine cognitive behavior" [Zhang 1997].

Aspirations: To some readers, both the notion of a telephone answering machine – and even a dedicated telephone – may seem rather dated. This invites us to imagine other roles Bishop's marbles and machine might serve. What if each marble represents a person (or in social media parlance, a "friend")? A group of people? A place, database entry, or computational operation? A dozen, thousand, million, or billion such referents?

Consumer product industry engagement: Philips vision of the future

Closely related to Durrell Bishop's work and other explorations at schools and universities, industry has also long explored the potential and consequences of computational technology for design and our everyday interaction with the world. Examples include the work of Interval Research [Cohen et al. 1999a; Singer et al. 1999a; Withgott 2015a], Apple ATG, Philips Corporate Design (PCD), and Oba Haruo's envisionments at Sony. To elaborate upon one example, within PCD, some concluded in the 1990s that changes within the field of electronic and digital appliances around the turn of the millennium were less likely to be the result of dramatic new innovation, and instead must be found in focusing, refining and merging of existing technologies in our everyday lives. One response to this outlook was the Vision of the Future project [Design 1995; Lambourne et al. 1997] (shown in Figure 1.9). The project lasted 1.5 years and resulted in 60 concepts and scenarios, communicated to audiences through short 30-90 second movies (45 in total), as well as via an exhibition showing a selection of the 180 models and simulations that were generated.

Concept: Philips' Vision of the Future explored scenarios of what products and services could exist in 2005, and how people respond to that regarding usefulness and desirability. The designs were developed based on social cultural trends obtained through two forecasting institutes, and technological trends that Philips was then developing. The designs were used as probes to explore potential futures using physical products, user interfaces, and context – both to enhance the quality of people's lives, and to raise questions and stimulate debate. Examples included:

- *Home, Heart, and Wants:* The Heart was envisioned to allow people to control home services including multimedia, temperature, security, and lighting. It was used in combination with the Want, a small handheld speech-controlled device.
- *Emotional container:* These handheld containers allow people to capture multisensorial messages existing of audio, video and scent, and give these as presents to colleagues, friends, and loved ones.
- *Bathroom:* Through networked equipment, this new bathroom facilitates information about the person's and families' health, aspirationally supporting a healthy lifestyle.

Design: The designs were created by a team of product designers, interaction designers, graphic designers, human factors specialists, exhibition designers, experts from the film industry, external consultants, and Philips Business Groups. Consequently, emphasis was placed on the look and feel of (interacting with) these products and services toward enhancing people's quality of life. The designs aimed to support adaptability to the person and situation. A simple, harmonious design language was used for all the products, whether medical, home appliances, or office-related. Where possible, the products made use of visual metaphors, relating them to

Figure 1.9 Vision of the Future by Philips Design [1995] *a) Home, heart, and wants; b) Emotional containers; c) Future desk; d) Bathroom*

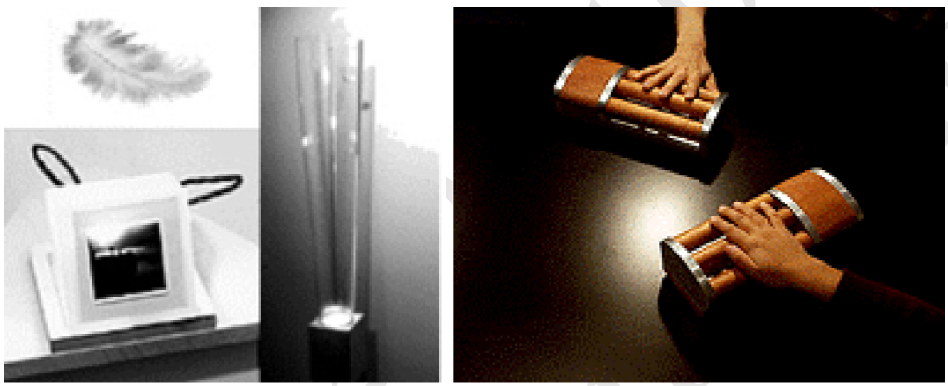

Figure 1.10 Expression in interaction: *a) Feather, Shaker and Scent [Strong and Gaver 1996]; b) InTouch [Brave and Dahley 1997b].*

familiar objects like watches, books, and picture frames, toward keeping distance from traditional PCs.

This latter focus was contemporaneous with other sister initiatives. Within the field of social computing and computer-supported cooperative work (CSCW) systems, most designs focused on functionality. Instead of emphasizing explicit, goal-oriented, informative communication, Strong and Gaver aimed to support implicit, personal, expressive communication [Strong and Gaver 1996]. Feather, Scent and Shaker (shown in Figure 1.10a) prototyped such expressive communication. They went beyond the physical metaphors of recognizability that Philips set as a starting point, and searched for poetry and richness in materials and expression. Similarly, inTouch (shown in Figure 1.10b) was developed by Hiroshi Ishii and his students Scott Brave and Andrew Dahley to explore the expressive possibilities of interpersonal communication through haptics [Brave et al. 1998b]. [Brave and Dahley 1997b; Dahley et al. 1998b].

Technology: The designs were based on technological trends that Philips was already developing or connected to. The technological starting points for this workshop were "improvements in computer power, software agents, voice recognition and synthesis, virtual reality, smart materials (e.g. liquids which increase viscosity in response to a stimulus), active plastics, remote-source lighting (allows light to be transmitted), light-emitting foils and polymers, global networks and telecommunications" [Design 1995; Lambourne et al. 1997]. Moreover, they aimed toward adaptability, learning, personalization, and customization.

Philosophy and cognition: Philips aimed to electronically and digitally augment their physical products. Their approaches can be seen to straddle and inform classic perspectives on rationality and representation with emotion and playfulness [Overbeeke et al. 2003a].

Aspirations: Philips expressed a vision where technology would be immersed within our everyday lives, where the boundaries between object and computer would evaporate; a vision close to Ubiquitous Computing [Weiser 1991a] and the Internet of Things (IoT) [Gershenfeld et al. 2004]. Many IoT devices continue to resemble traditional products (e.g. toothbrush, washing machine, thermostat); one can question prospective aesthetics for intelligence in the future. For example, in the context of automotives and mobility, concept cars are often used to envision the future (e.g., as with BMW's Concept Car Gina [Gavriluta 2017]). In particular, the birth of self-driving cars has deep implications for our perception of mobility. This offers great opportunities for tangible and embodied interaction, as illustrated compellingly by (e.g.) the 2016 Core77 Design Award recipient Stewart [Terken et al. 2017].

Augmented Reality and TEI for highly complex collaborative interactions

Also in the context of HCI, social computing, and CSCW, the influence of technology on mediating the interaction between users and their environment has long been explored concerning. For example, Mackay and colleagues explored how to augment our everyday working environment with technology, focusing specifically on air traffic controllers [Mackay 1999; Mackay et al. 1998](see Figure 1.11).

They aimed to develop an augmented reality (AR) environment for air traffic controllers by enhancing the paper flight strips that had been used for decades to control traffic.

Concept: In contrast to other electronic tools contemporaneously developed for air traffic controllers in which paper flight strips were replaced by electronic versions or discarded completely, Mackay and colleagues tried to maintain the paper flight strips. The existing system was in most respects safe and effectively employed the skills of the controllers. Consequently, their various designs augmented the strips, directly displayed information to the controllers, and explored the role of radar in their AR environment.

Design: Mackay's team experimented with a variety of solutions to investigate the potential of augmenting current air traffic control practices. Among multiple rationale, computer technology was not yet suitable to build a system where the flight strips could be fully used as interaction devices. Together with the flight controllers, they co-created new ideas through enacting (sometimes known as "informances" [Burns et al. 1994]) and Wizard of Oz techniques. This way, controllers could experience a variety of prospects for augmented strips; and Mackay's team could experience controllers' expert reactions to these design probes.

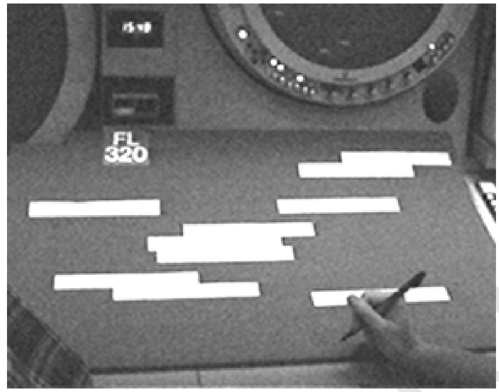

Figure 1.11 Paper flight strips for Air Traffic Control *[Mackay 1999; Mackay et al. 1998]*

Technology: Mackay and colleagues explored how information could be captured from the strips; how the location of the strips could be tracked; and how information could be presented onto the strips. In this search, they considered future technologies including electronic paper/ink [Howard et al. 1998; Jacobson et al. 1997; Negroponte and Jacobson 1997], eventually experimenting with technology that was already available. For input devices and information capture, they explored graphic tablets and pens, touch-sensitive screens, and video cameras. For presenting information, they turned to touch-sensitive screens, while also exploring video projection and graphical screens. For tracking information, they relied on video cameras as well as mechanical detents in the stripboard's strip holders.

Philosophy and cognition: The AR flight strips tool concept engages at least two forms of embodied cognition. First, it embraces distributed cognition. The spatial layout of the strips and their affordances for physical manipulation offload cognition during such stressful and time-sensitive activities. The strips enable a controller to make use of her visual and proprioceptive memory, supporting her maintenance of an overview of the situation, while having physical reminders of responsibilities regarding in-transit planes. E.g., sliding them to the left or to the right might indicate different conditions, which can be helpful when two planes are in conflict. Also, multiple controllers working together with different strips on the same stripboard foster collaboration, social coordination, and shared understanding of the situation. Thus, AR flight strips tool rely heavily on socially situated practice.

Aspirations: At the time, computer technology was insufficient to fully realize the proposed system (even in the lab). As modern and emerging technologies have progressively approached the AR flight strips vision, the underlying concept can be integrated in varied workplaces. During her TEI keynote talk, Wendy Mackay showed that the concept of AR air traffic control remains strong [Mackay 2015]. Per the concept of technological mediation, physical artifacts co-shape people as actors in the world by mediating the way that they perceive and act; and

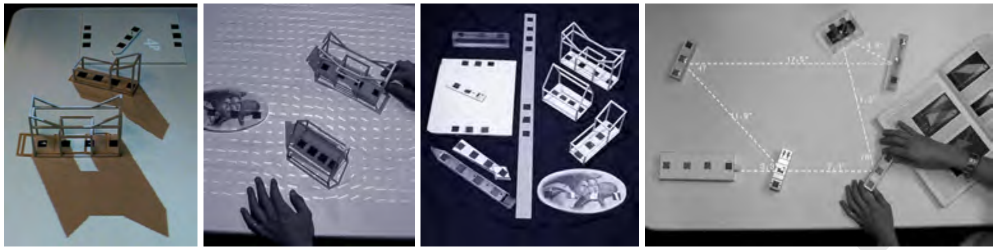

Figure 1.12 Urp *(John Underkoffler and Hiroshi Ishii, MIT Media Lab, 1999) [Underkoffler et al. 1999; Underkoffler and Ishii 1999a].*

the environment; and simultaneously, they reflect who we are [Verbeek 2006a]. Thus, new technological advancements also change our skills, open up possibilities, and facilitate new concepts.

Urp and the Luminous Room

Drawing from momentum at the MIT Media Lab (including the Things That Think/TTT Consortium) [Resnick et al. 1998; Small and Ishii 1997], Hiroshi Ishii's research within NTT Human Interface Lab [Ishii and Kobayashi 1992], the University of Toronto's Dynamic Graphics Project [Buxton, 2007; Cooperstock et al. 1995; Fitzmaurice et al. 1995a], Interval Research (leading later to [Cohen et al. 1999a; Singer et al. 1999a; Withgott 2015a]), and activities across academia and industry [Dunne and Raby 1994; Feiner et al. 1993; Hinckley et al. 1994a; Norman 1988a; Polynor 1995a; Weiser 1991a; Weiser and Brown 1996a; Wellner et al. 1993], Hiroshi Ishii and Brygg Ullmer coined the term tangible user interfaces in their 1997 *Tangible Bits* paper [Ishii and Ullmer 1997a]. One of the most compelling early expressions of tangible user interfaces is Urp - an interactive tangible urban planning simulator [Underkoffler and Ishii 1999a] (shown in Figure 1.12), which was developed by John Underkoffler while working within Ishii's Tangible Media group.

Concept: Within his "Luminous Room" concept, Underkoffler prototyped a number of working examples: luminous chess boards, bottle of words, a holographic workbench with numerous tangibles [Underkoffler 1999; Underkoffler et al. 1999]; and his most provocative and illustrative example, Urp [Underkoffler and Ishii 1999a]. There, each abstracted building-tangible, placed upon the luminous table, casts a shadow. When placed on the table, moving the physical hands of an inverse clock allows the virtual sun to be steered through the sky, thus enabling interactive shadow studies. A Renaissance-themed wind tangible, when upon the table, invokes and orients an interactive wind simulation, with animated winds racing through urban canyons. Wind probe, ruler, and material-selection tangibles allow complementary behaviors to be invoked.

Design: Urp's tangibles (shown in Figure 1.12) were made of foamcore (some surfaced with printed labels), extruded plastic tubing, and gel-filtered retroreflectors. The buildings were abstract, “wire-frame” structures, informed by aesthetic perspectives, allowing overhead projections to reach the table, and allowing embedded cameras to illuminate and monitor the retroreflective tags. The colored retroreflectors were primarily of technical necessity, but also served to label the tangibles as “special objects.” The Botticelli illustration of wind personified labeling the wind tangible is highly evocative, and to some suggested future prospects for (e.g.) jeweled variants of the otherwise spartan color tags. Beyond the physical design, Underkoffler’s flowing, smoothly animated projective mediations were also critical to impact [Underkoffler 1999; Underkoffler et al. 1999]:

> If the visual aspect of computation to date is theatrical... then visual design for the Luminous Room must be more like narrative filmmaking or cinema verite: graphical co-occupation of a world already filled with people, things, and assumptions.... The future of reactive, real-world graphics will surely have its own Rands and Tuftes, Leacocks and Gilliams....” [Underkoffler et al. 1999]

Technology: Underkoffler sensed tangibles through small, regular constellations of retroreflective dots, each faced with a red, green, or blue color filter. The tracking camera was roughly collinear with a light bulb. The retroreflectors allowed the spots to be discerned (thresholded for greater apparent brightness) from human skin and other visual elements. Custom software running on a late-1990s vintage SGI workstation was used both for computer vision, the simulations, and graphical mediation. A 2D lattice-gas fluid flow simulation (drawn from [Gershenfeld 1999]) was sufficiently simple to allow realtime execution on the hardware of the day, while sufficiently complex to allow evocative behavior.

Aspirations: The light bulb has long been a profoundly transformative technology. While artificial lighting’s mechanisms and pervasiveness have evolved since Edison’s 1879 public demonstrations [Wikipedia 2017], the concept, for the most part, has not. Both technically and conceptually, “I/O Bulbs” elicited a deeper expectation: that every “bulb” serves jointly as input, output, and computational mediator. If every room had several, or several hundred, “bulbs” – each sensing, transforming, and producing megapixels or gigapixels of light – what stories might such spaces have yet to tell?

Cubby

Around the turn of the century, the FormTheory group at the department of Industrial Design Engineering at Delft University of Technology explored tangible interaction, from within a stream of cognition theory - the ecological theory of perception by Gibson [Gibson 1979a; Norman 1999]. In Gibson’s view, we perceive the world as meaningful because of our bodily ‘fit’ with the world, and in terms of action possibilities [Overbeeke and Hummels 2013a]. The FormTheory group explored the potential of perception-action couplings for HCI, and how to bring technology into our embodied interactions in the world. One of the systems was Cubby [Djajadiningrat 1998; Djajadiningrat et al. 2001] (shown in Figure 1.13).

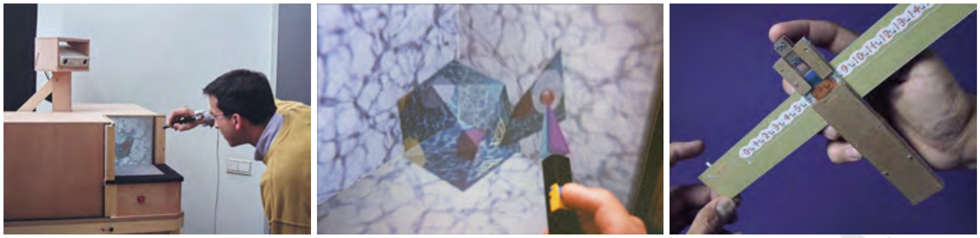

Figure 1.13 Cubby *(Tom Djajadiningrat, 1998): a) Cubby, a mini virtual reality cave; b) the hybrid tool used with Cubby [Djajadiningrat 1998; Djajadiningrat et al. 2001]; c) Heating controller [Djajadiningrat et al. 2004]*

Concept: Cubby was a special type of desktop VR system, used without goggles or glasses. By interlacing the display and manipulation space and making use of movement parallax (relating the visuals of the display to movements of the perceived via a reflector on the head), the digital world is perceived as stable and can be directly manipulated. The user can interact with this physical/digital world through hybrid instruments, physical bases, and virtual tips; e.g., one that behaves like tweezers.

Design: Cubby is a multiscreen movement parallax display for direct manual manipulation. To elicit sufficient information through movement, the digital environment has a rich texture to perceive space, similar to the way a haptically perceived pattern of a physical texture gives us information about its orientation and qualities.

Technology: Cubby consists of three perpendicular back projection screens in combination with three small video projectors with wide-angle lenses. The head position of the person is determined using an infrared head-tracker, and the projected images are updated in real-time to the head-position of the person using the fishtank VR projection method [Ware et al. 1993].

Philosophy and cognition: Cubby can be seen as an early example of embodied interaction. The consequences of ecological theories for design is compellingly illustrated when the user loses an object in "space" outside of the display, after dragging an object "out" of Cubby and releasing the grip of the hybrid tool. The object stays at the spatial position it is released, and can be grasped again later, even without seeing it in the display. The relation between the person and environment is constant; it does not matter if the object is digital or physical, or if it is displayed or not.

Aspirations: Embodied Interaction, as expressed by Paul Dourish and colleagues [Dourish 2001b; Williams et al. 2005], invokes embodied-being-in-the world theories from philosophers such as Heidegger and Merleau-Ponty to the world of computer science and HCI. Djajadiningrat and colleagues showed that the same principles apply not only to display systems, but also inspire other forms of appliances that are based on action possibilities, affordances, and skills (perceptual-motor, cognitive, emotional and social). Specific examples include heating controllers [Djajadiningrat et al. 2004], alarm clocks [Wensveen et al. 2004a], cameras [Frens

2006], and installations and educational toys for multi-handicapped children [Hummels et al. 2006].

Wearable Motherboard

TEI also often moves towards the body, with (e.g.) computers literally woven into textiles and apparel. In one work of this kind, Park, MacKenzie and Jayaraman [Park et al. 2002] developed the Georgia Tech Wearable Motherboard (GTWM) (shown in Figure 1.1.9).

Concept: This E-Textile merges computing and textiles. With the Wearable Motherboard, Park et al. aimed to develop personalized mobile information processing (PMIP). This resulted in a computational fabric network that can be worn by the user, offering her many possibilities through the underlying sensing, monitoring and information processing capabilities.

Design: "The fabric is the computer." For developing this E-Textile, Park and his colleagues focused mainly on the technical possibilities, material qualities, and (functional) potential it can have for users, developed in a way that can be worn.

Web companion 1.4 (ch1/figs/a4)

Wearable Motherboard vest and controller [Park et al. 2002].

Technology: GTWM incorporated optical fibers and sensors to monitor bodily vital signs of the wearer. A flexible data bus transmits body signals to monitoring devices including an EKG Machine, temperature recorder, voice recorder, etc. A "switchbox" approach is used to combine the conductive fibers into a programmable network. Switching components can be added at strategic intersections to the field-programmable gate arrays linked to the conductive fibers.

Aspirations: New manufacturing techniques make "soft electronics" possible, thus offering new possibilities and affordances for TEI. These wearables can sense wearer and environment, offer new possibilities for personal and socio-cultural expressions, enable different forms of interpersonal communication, and give new ways to interact with the world. GTWM focused mainly on the technological and materials qualities and possibilities of this new form of interaction. Related fields have been exploring the possibilities of wearable technology and E-Textile for and on the body such as affective computing [Picard 2003], quantified self [Swan 2013], somaesthetics [Höök 2018a], and Smart Textile Services [Kuusk et al.].

Beginning to generalize

These example systems are not the first human activities to entangle physical artifacts as representations and controls for varied associations. Rather, they offer a very small sampling of examples building upon millenia of grounding progress. Figure 1.1 summarizes a few such examples extending throughout human (pre)history.

Beyond their histories as individual pioneering examples, the examples we have considered allow us to begin generalizing thematic commonalities. We consider these now through the facets we have thus far highlighted, before later revisiting these at greater length.

Concept: Tangible interfaces, in these beginnings and continuing to the present, have often been professionally motivated. The building blocks system, universal constructor, and Urp all drew from the architecture domain, a domain rooted in the physical world and with a long tradition of engagement with physical models. Other systems, in early days and since, have frequently engaged other professional applications. Domestic contexts have also been active areas of academic and industry consideration, as illustrated both by the Marble Answering Machine itself, and its vision of a broader ecology of interacting products. Educational contexts in general, and work with younger children in particular, have also been among the most common tangible interface application drivers.

Design: The physical and visual design of tangible interfaces sometimes engage relatively minimalistic, abstract forms; but also employ diverse expressive, representational styles (e.g., Urp's Renaissance-themed wind tangibles). Tangibles sometimes are realized as individual or sets of simple geometries such as cubes, spheres, and cylinders, often in modal sizes (e.g., cubes of 5cm or 10cm sides which likely draw from human hand anatomy and grasping postures). But equally often, representation is approached as models or miniatures of other systems (e.g., Urp's buildings); or as newly conceived and expressed forms (e.g., the marble answering machine and slot machine). The physical mediums of tangibles sometimes employ the plastics and prospectively mass-produced forms common among consumer electronics; but also wood, paper, cloth, and other more organic and (sometimes) evanescent materials, sometimes in fashions explicitly aspiring to hand-crafting.

Technology: The marble answering machine, slot machine, building blocks system, and universal constructor illustrate pursuit of computational and networking integration within appliances and products (e.g., the Internet of Things [Atzori et al. 2010; Gershenfeld et al. 2004]). Conversely, they can be regarded as progression of computational, communication, sensor, and display technologies into diverse physical contexts (e.g., ubiquitous and pervasive computing [Reilly et al. 2010; Weiser 1991a]). Some of these enabling technologies are embedded within the tangibles themselves; some within proximal computers or computational devices (desktops, laptops, smart phones, etc.); and some within the physical environment (e.g., walls, floors, and ceiling lamps). Some of the enabling computation and data is proximal; others, prospectively in remote network and cloud contexts.

Cognition: Tangible interfaces are sometimes oriented toward individual users, but are more often shaped by distributed cognition involving a plurality of people (sometimes copresent in space and time, sometimes not). When engaging multiple people, those individuals may have common experiential background. Alternately, group work, recreation, and domestic contexts between people of diverse experiences and perspectives are at least (if not more) common – sometimes explicitly in formal or informal education contexts, others driven by communication

Figure 1.14 ReacTable [Jordà 2010; Jordà et al. 2007].

and cooperation more generally. TEI systems are sometimes oriented toward "layperson" in general; but often to specific populations – the very young and old, or individuals with physical or cognitive disabilities.

More recent examples

As this book's first edition was completed, more than three thousand tangible interfaces had been published academically, and many commercialized in industry (with more every month). We will describe dozens of these examples throughout the book. To consider several initial illustrative present-century examples, we next briefly discuss ReacTable, Sifteo, SMSlingshot, and TRANSFORM.

Reactable

Concept: The Reactable system [Jordà et al. 2007] aims to enhance interactive, collaborative and real-time electronic music production (see Figure 1.14). The system was designed and developed by a research team, originally from the Pompeu Fabra University in Barcelona. Sergi Jordà, Günter Geiger, Martin Kaltenbrunner and Marcos Alonso presented Reactable for the first time in a public concert at the International Computer Music Conference 2005 in Barcelona. In 2009 they founded the company Reactable Systems [rea] to further develop and distribute the Reactable and related instruments.

Reactable consists of a round interactive tabletop display and a set of tangible pucks. Each puck represents a modular synthesizer component with a dedicated function for generating, modifying or controlling sound. By grasping, placing, and manipulating the pucks upon the table, users construct different audio topologies using a graspable flow-controlled programming language. The system is inspired by 1980s modular analogue synthesizers, but is re-imagined with easier and more intuitive controls that allow for rapid and collaborative electronic music production. The Reactable has been deployed in numerous concerts, museums, and public spaces, and have been used by children, casual and professional musicians.

Design: The Reactable tabletop is a translucent surface, its round form factor encourages multiple performers to engage with the interface at the same time, providing no privileged points-of-view or points-of-control. The design is inspired by Hornecker and Buur's articulation of the social interaction and collaboration dimension of tangible interaction [Hornecker and Buur 2006a], as well as by Gaver et al. design for ludic activities, activities motivated by curiosity, exploration, and reflection rather than externally-defined tasks. Lessons for ludic design include offering a range of possibilities for people to explore, presenting the familiar as strange and the strange as familiar, and avoiding the appearance of a computer [Gaver et al. 2004].

The Reactable interface is controlled by manipulating acrylic pucks on its surface. When a puck is placed onto the tabletop it becomes illuminated, and interacts with other pucks in its vicinity based on their function, relative positions and proximity. To support computer vision recognition each puck is marked with an amoeba fiducial marker [Kaltenbrunner and Bencina 2007a]. These markers were designed both for recognition and aesthetic decorative appeal. The markers have an organic appearance and are integrated into the overall visual design of the complete interface. Users can rotate and connect pucks to one another to combine different elements, like synthesizers, sample loops and other audio effects. These interactions are...

Professor Martin Kaltenbrunner, University of Art and Design Linz, Austria: Share your tools!

Imagine the times when human-computer interaction made the shift from text-based terminals to graphical user interfaces. This innovation process started with early computer graphics and direct manipulation interfaces, which very quickly converged into the desktop computer interface we are all familiar with today. Researchers and developers not only created the GUI concepts, metaphors and prototypes, but also shared the necessary programming languages and application libraries which eventually became the foundation of most standard operating systems. Today the research and development around tangible user interfaces may constitute a similar shift towards new human-computer interaction paradigms, which have been inspired by a now common vision of tangible bits and radical atoms. This vision drives a community with an astonishing output of novel interaction concepts, speculative design and technical innovations. The alchemists of tangible interaction design may feel like renaissance scientists, which shape their own tools in order to create their multidisciplinary art and craft. On the other hand, without sharing our tools we rather may seem like GUI developers without any application library, who have to draw each single interface element from scratch every time, before they can concentrate on the actual research and development task. While constantly pushing the boundaries of how we can enrich our physical environment through embodied digital information, we also seem to forget about the consolidation of more than two decades of valuable research and development results. This consolidation process can only be achieved through a shared effort that continuously collects and integrates these innovations into an open source hard-and software libraries, which are also embedded into robust theoretical frameworks. Our publication practice needs to be extended from the mere written documentation of research methods and results towards the inclusion of source code, research data and physical designs, which allow the complete recreation, scientific evaluation and eventually an innovative extension of that research. Tangible user interfaces are of course more diverse and complex than conventional desktop computer interfaces, but some particular genres such as tangible tabletops or constructive assemblies had already been implemented within open source frameworks and even commercial platforms. When developing the Reactable synthesizer, there wasn't any platform available that would allow the development of such a tangible tabletop application at that time. Thus, in order to design and build a novel musical instrument, the full ecosystem for a tabletop hardware and software framework needed to be created first. The resulting open source Reactivision and TUIO framework later enabled many designers and researchers to create their own interaction tabletop applications, while the Reactable became a commercial musical instrument for performing artists. Open source technologies and their commercial implementations are not mutually exclusive and are both valid approaches for a shared innovation culture – the only important aspect in this context is their general availability in order to inspire and foster further innovation. A common culture of shared tools cannot be driven by individual research groups only, but needs a collective effort of the whole TEI community.

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...immediately projected on the table surface, making music production both visible and tangible. The pairing of a graphic display with tangible manipulation features the performative aspect of electronic music production, through real-time physical control and visualization.

Technology: The Reactable uses the reacTIVison computer vision framework [Jordà et al. 2007] to track finger touches and objects tagged with fiducial markers. The visual feedback is displayed on the surface via a short-throw projector stored inside the table. reacTIVision is an open-source cross-platform computer-vision framework, which was designed for the construction of table-based tangible user interfaces. The framework provides a standalone application for fast and robust tracking of fiducial markers in a real-time video stream, as well as defines the communication protocol TUIO [Kaltenbrunner 2009a], which was specifically designed for encoding and transmitting the attributes of tangible artifacts found on a table surface.

Cognition: The creators of Reactable depicted "a fertile two-way cross-pollination situation that can equally benefit both fields [music performance and HCI]", highlighting entanglements of Art and STEM disciplines (STEAM). Inspired by early examples of synergy between music and HCI, as demonstrated by the work of William Buxton during the 1970s and 1980s [Buxton 1997; Buxton et al. 1982], they emphasize that "there are important reasons, perhaps often more intuited than stated, that turn live music performance and human computer interaction (HCI) in general, and musical instruments and tabletop tangible interfaces in particular, into promising and exiting fields of multidisciplinary research and experimentation" [Jordà et al. 2007]. The Reactable brings physical performance back into live computer music production, allowing for expressivity, control and collaboration, and pushing boundaries on what one can achieve musically. It broadens the reach of electronic music production, allowing for both planned and improvised concerts performed by casual or professional musicians. The system facilitates the creation of live performances that are interesting and exciting to watch, as evidenced by the millions of views on YouTube of a Reactable demo and Bjork's use of the Reactable during one of her world tours.

Aspirations: Music performance combines expression, precision, creativity, and entertainment [Jordà et al. 2007]. It is also one of the densest forms of human communication [Bischoff et al. 1978]. Reactable combines tangible control with sound and visual output to provide a rich experience with a wide sensory bandwidth. Creating and playing live music requires "a very precise temporal control over several multidimensional and continuous parameters, sometimes even over simultaneous parallel processes is specially required in the interaction dialog that takes place between the performer and the instrument" [Jordà et al. 2007]. Reactable abstracts away some of the low-level details associated with making electronic music (e.g. storage, and code), allowing users to focus on higher levels process. Using spatial awareness and bi manual interaction users can monitor and control continuous and parallel processes. This creates a dialogue between the user and the instrument (ReacTable), crafting a "shared performance" as the performer delegates control to the instrument [Jordà 2010]. Reactable also supports the socially situated practice of collective music making, enabling collaborative construction of meaning during live performances [Jordà 2010].

Siftables and Sifteo Cubes

Concept: Most tangible interfaces we have considered have centered on physical artifacts that are either physically passive (containing no active electronics), or limited in their display capacity (as with the LED-embedded cubes of Frazer). In contrast, Siftables [Merrill 2009] (as an academic prototype) (see Figure 1.15a) and Sifteo Cubes (as a commercial product) (see Figure 1.15b) were faced with pixelated LCD displays. Cube sets could be bound to many dozens of available applications, which were typically driven by the composition, decomposition, and recomposition of Cubes. Cubes could identify neighboring cubes – both horizontally, and when stacked vertically; and could sense screen-touch and orientation. While most Cube applications were games [Geurts et al. 2014; Merrill et al. 2007, 2012; Merrill 2009; Pillias et al. 2014; Sajjadi et al. 2014] or educational [Falcão and Price 2012; Goadrich 2014; Ku et al.

Figure 1.15 Siftables and Sifteo Cubes [Hunter et al. 2010; Merrill et al. 2012].

2014], some also explored engagement with scientific domains [Chang et al. 2012], databases [Langner et al. 2014], and health [Claes et al. 2015].

Design: The design for Siftables seeks to leverage people's natural skills of physically sorting and sifting through large quantities of small physical objects, like when looking through a stack of photographs. Siftables explores how sensor network technologies can integrate components of graphical and tangible user interfaces without relying on an external infrastructure for delivering graphical output, which in turn increases the directness of users' interactions with digital media. Siftables is a collection of compact tiles (36mm x 36mm x 10mm), each fitted with an LCD screen and various sensors. The small and compact form factor affords grasping and physical manipulation of the tiles. Each tile can sense its own motion and interactions with other tiles, as well as gestures such as lifting, tilting and shaking. Visual feedback is displayed on the embedded LCD screen in response to the user's physical manipulation of the collection. Similarly Sifteo Cubes, the commercial product based off the Siftables research project, is comprised of embodied physical blocks. The block form factor enables rapid manual arrangement, encourages creative interactions, and increases accessibility since it appeals to a wide range of ages and skill levels. This design also encourages collaboration and multi-player interaction.

Technology: Siftables and Sifteo Cubes passed through several major iterations. In the original research prototype Siftables [Merrill et al. 2007], Merrill describes three major design generations and an implemented hardware platform [Merrill 2009]. In this version, neighboring Cubes communicated with each other via infrared signalling (four transponders per cube), and each Sifteo could communicate via Bluetooth (RF) with a host computer. On the host personal computer, a Python API was used to implement actual applications. The first commercial version of Sifteo cubes mirrored this approach, again with dependency upon a host PC, but with inductive (RF) near-field communication between neighboring cubes. In the second commercial version of Sifteo cubes, the dependency upon a host PC was eliminated, with games (and other applications) running directly upon a sibling electronic block.

Cognition: The design of Siftables was inspired by the human skills of sifting, sorting, and manipulating large numbers of small tangible objects. With Siftables, users can apply physical and spatial manipulations such as stacking, grouping, flipping or shaking, to test hypotheses and represent knowledge. The idea of combining physical actions with internal thought processes, is central to the theory of *distributed cognition* [Hutchins 1996], which views thinking as a process which combines internal and external representations. The distributed nature of Siftables allows for shared control, enabling multiple users to engage in a multi-player activity. The visibility of the physical actions and spatial configuration facilitate *group awareness*, by allowing users to see what others are doing and interpret the knowledge encoded by the spatial arrangement of the blocks.

Aspirations: The commercial Sifteo cubes were created to engage users with games and learning activities through physical exploration and spatial reasoning. The product aimed to help users solve problems by understanding and manipulating spatial relationships of physical objects, and facilitated the development of numerous games for various age groups. Sifteo cubes also offered TEI researchers a novel prototyping platform for exploring tangible interaction with *active tokens* - programmable physical objects with integrated display and sensing. Sifteo provided an accessible API combined with distributed networked physical platform, which allowed researchers to experiment with a wide range of novel concepts.

SMSlingshot

Concept: The SMSlingshot (shown in Figure 1.16) is a project developed by VR/Urban, a collective of public media interventionists that aims to reclaim screens in public places [Fischer et al. 2013]. The project encourages interactions with large media façades and the built environment, and simultaneously creates a digital space in which the public can "speak up." SMSlingshot builds on humans' longtime desire to comment on their surrounding environment, and allows people to articulate themselves in a similar fashion as big advertisers. It is an embodied interface that encourages social interaction and multi-user play. This project is both a conceptual art piece and a political vehicle to express protest narratives in urban spaces.

Design: SMSlingshot is a Media Façades installation, which is deployed in an urban environment. It consists of a wooden slingshot embedded with a keyboard and a mobile device. First, the participant types a message using the wooden keyboard. Once the message is typed, the user pulls on the flexible ribbon to activate a laser beam, which creates a green dot on the façade so that the user can select their target. Once the user has elected their target and released the ribbon, the message is sent to the computer and is displayed in a colorful splat on the wall, at the target point. The project is a mixture of high and low tech mediums and aesthetics. To enhance the magical experience of the SMSlingshot, most of the technology has been obfuscated to recede to the background. The form factor borrows from one of humanity's oldest tools, re-imagined for flinging virtual content.

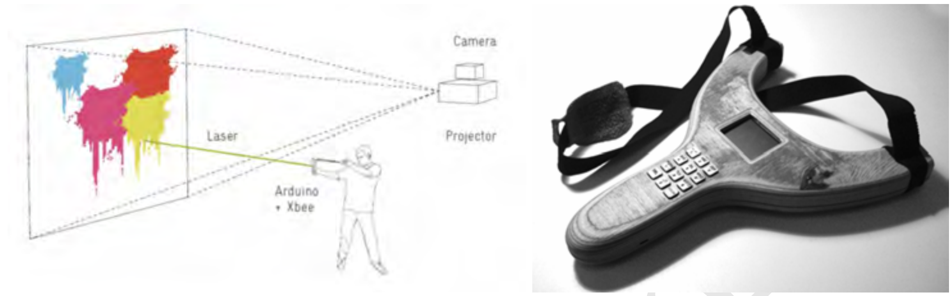

Figure 1.16 SMSlingshot [Fischer et al. 2010].

Technology: The SMSlingshot is comprised of an xBee transmitter, ATmega328 microprocessor, LCD display, green laser module and batteries. The text messages are typed on a wooden keyboard, modeled after a phone dial pad, that is integrated into the wooden slingshot case. Behind the scenes, a camera detects the laser point on the façade while a laptop runs the SMSlingshot software and the laser detection program. A radio modem receives the information from the slingshot and a projector displays the visuals on the wall. The 'in the wild' deployments of the SMSlingshot pushed the implementation towards product-nearness, accomplishing the robustness required from the environment.

Cognition: SMSlingshot uses an *embodied metaphor* to relay the conceptual idea of reclaiming public space by occupying a façade with personal virtual messages. The physical actions of holding the device, typing a message, aiming, pulling and releasing, followed by the impact of these actions as a personal message splashes a public façade generated suspense and joy. Participants handles the slingshot with "a mixture of familiarity, intimacy and expressiveness."

Aspirations: The SMSlingshot engages ubiquitous technological medium (text messaging) to counteract the passive consumption of advertising shown on the increasing number of commercial screens found in urban environments. More broadly, it explores empowering people to create and display augmented reality content in their built environment. This is a prospect toward immediate realization of user-generated virtual content in arbitrary spatial contexts.

TRANSFORM

Concept: Created by Professor Hiroshi Ishii and MIT's Tangible Media Group, TRANSFORM (shown in Figure 3.4) morphs static furniture into a dynamic machine driven by a stream of data and energy [Ishii et al. 2015a]. TRANSFORM embodies Ishii's vision of "Radical Atoms"[Ishii et al. 2012a] - human interaction with dynamic, computationally transformable shape-changing materials, which shift their physical state to reflect dynamic changes in digital information. The project aims to surprise and inspire viewers with unexpected transformations, as well as reveal the mechanisms of a complex machine in motion. TRANSFORM's movement

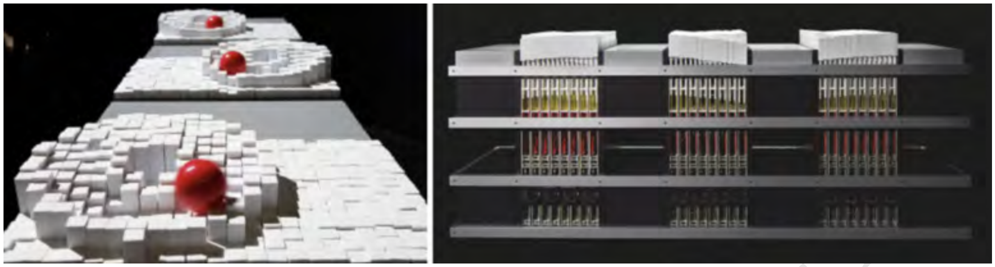

Figure 1.17 TRANSFORM *(Ishii, et al., MIT Media Lab, 2014): [Ishii et al. 2015a]*

reflects viewers' kinetic energy captured using sensors, which is represented on the table interface through the motion of dynamic pins. The interface has potential to be an effective tool for storytelling and artistic expression given its ability to communicate ideas via the power of dynamic computation and tangible representation.

Design: TRANSFORM is a custom built table interface embedded with three inFORM shape displays [Follmer et al. 2013a]. Each inFORM display has 1,152 pins (24 x 16 pins) that shift up and down in real-time to reshape the tabletop into a dynamic display. The inFORM engines are integrated into the table with the technology fully exposed, so that the pistons and wiring are visible. The motion of the interface was inspired by: dynamic interactions between wind, water and sand in nature; Escher's representations of continual motion; and the ephemeral qualities of sand castles built by the sea. TRANSFORM has three representational modes: Wave, Machine and Escher. Wave mode allows users to interact with the interface via gesturing with their hands, arms and bodies. The Machine mode is pre-programmed and illustrates the story of "Nature and Machine." The Escher mode displays "inter-material interactions" between an inert red ball and the inFORM pins.

Technology: TRANSFORM has actuator modules, each with with 12 x 12 pins that extend up to 100mm from the surface. Modules can be combined to make larger shape display surfaces. Integrated into the hardware are custom Arduinos that run a PID controller to sense the position of six connected pins. The pins are moved via motorized slide potentiometers. The slide potentiometers are mounted onto a custom printed control board. To allow dense arrangement of the pins, Push-Pull rods link each pin with an actuator. Six buses bridged to a USB allow the boards communicate with a PC, which runs the TRANSFORM application. The application is built in C++/OpenFrameworks, and can support 3D models and grayscale images, that are rendered as a depth image, and transferred to the shape display over a USB connection. A Microsoft Kinect is mounted 4m above TRANSFORM to detect visitors' gestures and arrival at the table.

Cognition: TRANSFORM, and the InFORM shape displays it consists of, draw upon the rich history of affordance in Human-Computer Interaction [Gaver 1991a; Gibson 1979a; Norman 1999]. The system seeks to utilize dynamic affordance, which can transform shape, size, location and orientation, as well as appear and disappear. Such affordance can be perceived both visually - e.g. by creating a shape of a 'play' button, and tactilely - by guiding the user's motion through physical transformation [Follmer et al. 2013a].

TRANSFORM and InFORM also introduce dynamic constraints, which mediate interaction between the interface and tangible tokens or tools [Follmer et al. 2013a]. Dynamic constraints provide guidance to users, by limiting the degrees of freedom through which they can interact with the system. Dynamic constraints also physically restrict the motion of tangible tokens placed upon the interface. Dynamic constraints builds on and expand frameworks of Token and Constraints for tangible interaction [Shaer et al. 2004a; Ullmer et al. 2005a].

Aspirations: TRANSFORM pushes the boundaries of traditional furniture design aesthetics through the fusion of design and technology, and the exploration of the aesthetics of dynamic objects. While developed with furniture design in mind, TRANSFORM embodies the vision of Radical Atoms [Ishii et al. 2012b], imagining future human-material interaction with materials that can change form and appearances dynamically. TRANSFORM's shape displays can be viewed as "digital clay" - malleable material that is synced with an underlying digital model, and could be directly manipulated by users' hands.

Reprise

Rounding out our tangible beginnings, we consider two additional perspectives for contemplating computationally-mediated tangibility.

Tangible paradigms

Bill Verplank served as an early leader in designing computational systems at Xerox [Johnson et al. 1989] and IDEO, and an early creator of tangible interfaces at Interval Research [Cohen et al. 1999a; Singer et al. 1999a]. In his paper *"Interaction Design Sketchbook"* Verplank [2009] introduces a framework for designing interactive products and systems, existing of 4 parts: sketching, interaction, design and paradigms. *"The design of human-computer interaction has been organized around competing beliefs and professional establishments. It is important to realize how insular each of these paradigms can be and to consider how to cross paradigms"* [Verplank 2009]. Verplank is inspired by the *extensions* concept of McLuhan [1964], indicating that an interaction problem is presented by everything that comes between my environment and the person. For example, electronics are extensions of our senses (media) and clothing is an extension of our skin (fashion). Based on the concept of extensions, Verplank [2009] introduces six paradigms (summarized in the left column of Figure 1.18), where computers are seen as the following metaphors:

- *electronic brains* (referring to, e.g., agents and recognition),
- *tools* (referring to, e.g., tools, tasks, use and HCI),
- *media* (referring to, e.g., multi-media, the web and "being digital"),

- *life* (referring to, e.g., artificial life and chaos),
- *vehicles* (referring to, e.g., standards, infrastructure, super-highway),
- *fashion* (referring to, e.g., wearables)

The successive columns of Figure 1.18 explore how Verplank's paradigms intersect with the exemplar interfaces discussed in this chapter. For each interface we specify a principal paradigm (denoted in dark gray) as well as secondary paradigms (denoted in light gray). Most of the exemplar interfaces can be seen serving as *tools* which seems to make absolute sense considering the emphasis on tangibility to be able to directly manipulate these interactive artefacts as tools, e.g., the marble and slot machines as *tools* for operating on marble and card *media*; or the ReacTable as *instrument/tool,* operating upon and "through" its "control" and "sound objects" (as *media*); or Cubby as *tool/environment* to interact with and operate on virtual objects displayed in this mini Virtual Reality Cave; or the Air Traffic Control as *instrument/tool,* to get a spatial and time-related augmented overview of the different paper flight strips representing the different flights; or the Philips Vision of the Future designs as *daily objects/tools* for interacting with our home and performing our job (as *media*) as well as expressing ourselves (as *fashion*). Among Verplank's paradigms, the "media" role is suggested as principal for three exemplars (BBS/Universal Constructor, Urp, and Sifteo). In each of these, tangibles serve as persistent expression of the "key objects of interest" [Ullmer 2002], with these tangibles offering themselves as a medium of expression and use.

The SMS Slingshot clearly could be argued a *tool* (for operating upon intangible messages). But viewed through Verplank's lens, it is perhaps more interesting and evocative to regard it as a *vehicle*, through which access to the otherwise inaccessible (remote façades) can be navigated. Perhaps similarly, the TRANSFORM platform can clearly be regarded as a tool; but both through its animatronic vitality, and through its examples as an actuated medium of tangible telepresence, Verplank's *life* paradigm/metaphor seems more suggestive. The Wearable Motherboard, where computers are woven into fabric and apparel, strongly fit the *fashion* paradigm.

Medium and message

Contemplating the widely divergent messaging and dynamics of newspaper, radio, and television during the 1960s, Canadian philosopher Marshall McLuhan posited "the medium is the message" [McLuhan 1964]. In the realm of tangibility, consider wood and fabric, metal and plastic, leather and glass, paper and pylons, pasta and bone, straw and stone. Each of these physical mediums brings its own world of 10,000 diverse variations; woven into human employment through 10,000 disparate cultural vantages.

Tangible interfaces offer the prospect of awakening from their slumbers, fired by the powers of computational mediation, this universe of existing physical expression. Tangibles also speak equally to new worlds of novel forms distinctly reflecting their hybrid heritage. Hybrid, for as

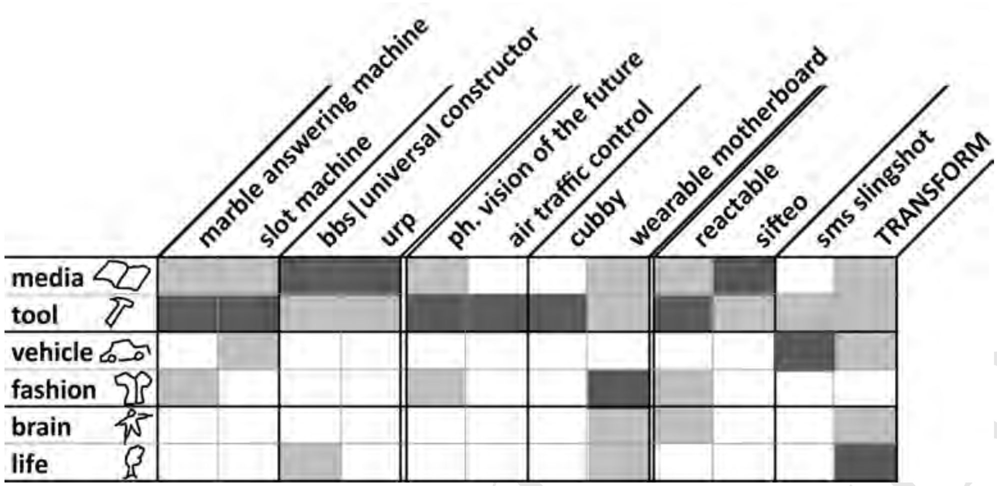

Figure 1.18 Verplank [2009] **discerns six computing paradigms**, regarding computers as different metaphors, more specifically, as media, tool, vehicle, fashion, brain or life. When classifying our tangibles exemplars, we see that most of the artifacts consider the computer to be a tool (the principal paradigm is denoted in dark gray), followed by the metaphor of media. Moreover, most artefacts are not specified by one paradigm/metaphor, but by multiple (the secondary paradigms are denoted in light gray)

critical the role of the physical medium, the interwoven computational and (often) electronic mediums are equally central.

For screen-centric computational interfaces, *transience* is arguably one of the central modalities and messages, with one moment's occupant of virtual real estate swiftly yielding to the next. Conversely, *persistence* is a central consequence and distinction of tangibles' physicality (though this takes an altered stance in actuated systems such as TRANSFORM). Understanding and optimizing the tradeoffs attendant with persistence is a major theme of this book.

We would also note that several of our examples deeply integrate active electronics within tangibles (Sifteo, SMSlingshot) or within some element of the system (Slot Machine, Universal Constructor, Wearable Motherboard, TRANSFORM). Noted researcher Ken Hinckley (whose 1994 "passive props" was perhaps the earliest tangible interface published within the flagship ACM CHI conference [Hinckley et al. 1994a]) has said "changing hardware changes all the rules" ([Hinckley and Sinclair, 1999]). This practice of bending the form and function of one of the most general-purpose of instruments to task, data, or person specificity – is one of the great prospects, promises, and potentials of tangible interfaces.

Many other mediums can be seen as implicitly and explicitly engaged by tangible interfaces, including architectural, wearable, edible, biological, and compostable interface genres. These and many others are stories of the coming pages.

Enodia tangibles

Each of the authors has taught TEI in university settings for two decades or more. While TEI can be approached in many ways, each of us highlight student projects in our teaching. Over the decades, in our projects and courses, many products and technology toolkits have come and gone – IRC11, iRX, Crickets, Dacta, iCube, Phidgets, Blades and Tiles, iROS, Zowie, Sifteo, and many others. None of these remain common; and few well-support the majority of ideas we will investigate in this book. If there were a specific technology platform we could identify with confidence that it would exist in well-supported form years into the future, this would be attractive.

In response, building upon approaches that have been successful in other computing communities (e.g., operating systems), in partnership with the "Enodia[4]" US NSF-funded research project (NSF MRI CNS-1828611), we will relate our discussions to a series of open-source tangibles at several points in the book. These Enodia tangibles have been co-developed both for minimal-resource realization by our students and users of this book; and for many-screened and VR interactive computational (ICy) STEAM (Science, Technology, Engineering, Art, Technology, and Math) research use [Ullmer 2015]. We see strong synergism between classroom and applied research use. This reflects the central implementational roles students often serve for STEAM research.

Figure 1.19 Several views of Enodia tangibles: hextoks, hextok interaction devices, Ferntor Shelter

Several illustrations of these Enodia tangibles are in Figure 1.19. The first of these (in partnership with Dr. Alexandre Siqueira) came from a collaboration between a number of researchers at the 2019 Dagstuhl (Germany) seminar on Ubiquitous Computing Education (19232) [Kun et al. 2020]. There, 28 researchers, focusing on varied topics relating to diverse aspects of ubiquitous computing, AR, TEI, etc., gathered and sought common ground. This first

[4] In Greek mythology, Enodia watched over entrances, standing on the main road into a city, and in the roads to private houses. She also was associated with crossroads, light, and passages between ~worlds.

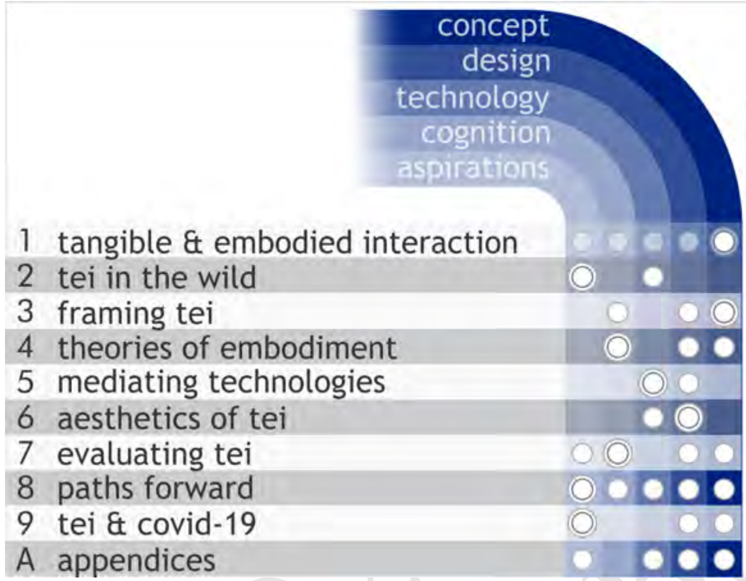

Figure 1.20 Book structure, viewed in context of tangible exemplar facets

set of illuminated hexagonal tokens was co-designed by participants Ullmer, Shaer, Konkel, Rinott, Mills, and Zeamer to interactively illustrate our diverse, yet widely intersecting, set of classroom (and research) activities. The latter of these illustrations show how a mediated version of these hexagonal tokens has been implemented and applied to several example domains.

We provide and engage these Enodia tangibles in several forms. One form is through a series of 3D models (natively expressed in the free Blender environment). Secondly, we provide a series of physical elements for fabrication. Our simplest tangibles integrate low-cost NFC/RFID tags that can be read by smartphones. We provide further integration of this to the Raspberry Pi Zero (and Zero W, which includes WiFi) Linux-based board.

With these two boards, the tangibles we describe can be sensed, and output relayed to proximal screens. We also provide successive variants which integrate speakers; ePaper; LED illumination; and many other sensors. We provide demonstration mappings of these tokens for engaging with a number of application domains, including the United Nations Sustainable Development Goals; several books, including this one; several recorded and streaming media sources; and others. These are elaborated in Chapter 5 and in the Appendix; and are further supported through a companion web site.

Structure of the remaining chapters

The "concept, design, technology, cognition, and aspirations" facets we have considered for our exemplar interfaces also map roughly to the structure of this book. Figure 1.20 summarizes our chapter titles as rows, and these facets as columns. Double-circles indicate the principal topic; regular circles, topics of substantial engagement. The introductory and concluding chapters are crosscutting in nature; the remainder chapters, each spotlight an individual facet, interwoven with one or more contributing facets.

Next, we turn to TEI in the Wild, focusing on the aspirations of TEI to engage with various application domains, and to create positive impact on individuals and communities.

2 TEI In The Wild

In the first chapter, we introduced the concepts of tangible and embodied interaction through the review of historical and cultural tangible precedents, as well as contemporary examples. We considered these examples from the perspective of concept, design, technology, cognition, and aspirations. In this chapter, we focus on the momentum and aspirations of TEI toward engaging several major application domains, creating positive impacts for individuals and communities.

As we completed the first edition of this book, thousands of tangible and embodied interfaces have been published academically, and many systems commercialized in industry. Here, we survey dozens of these deployed examples, focusing on interfaces that were deployed and evaluated "in the wild" [Rogers and Marshall 2017] within real-world settings, including homes, classrooms, and indoor and outdoor public places.

In particular, we survey three dominant application domains: learning, social connectedness, and health and wellbeing. However, these application domains are neither mutually exclusive nor exhaustive, as we have seen a wide expansion of tangible that cross domain boundaries and address novel use scenarios. When possible, we will indicate sister surveys, which further focus on particular application areas. For example, Shaer and Hornecker's survey of application domains for TEI covers additional application domains [Shaer and Hornecker 2010b], which we do not survey here. Our goal for this chapter is to demonstrate how the theory and practice of TEI can be applied to make a difference in the real world.

Learning

Numerous TEI systems have been designed to enhance learning and to augment learning environments. To date, TEI systems have been adopted as educational toys and computer-supported learning tools in homes, classrooms, and museums, encompassing a wide range of content domains ranging from STEM (science, technology, engineering, and math), to literacy, art, history, and heritage.

The unique properties of TEI systems have compelled designers, researchers, and educators to apply TEI approaches to learning. For example, the concrete, multisensory nature of tangible interfaces make them accessible to children at different developmental stages [Antle and Wise 2013a; Bers and Horn 2010; Marshall 2007b]. Tangible and embodied interfaces also promote hands-on engagement while facilitating exploratory, expressive, and epistemic actions [Marshall 2007b; Price et al. 2008]. Additionally, tangible interfaces support collaboration by providing multiple points of entry to an activity [Hornecker and Buur 2006c], allowing learners to share and exchange objects as well as to observe others [Okerlund et al. 2016].

The Tangible Learning Design Framework [Antle and Wise 2013a] discusses these and other features of TEI systems that are important to consider in learning contexts, and provides design guidelines that draw upon cognitive and learning theories to inform specific design choices. The framework also highlights research questions about how and why TEI design is expected to affect learning. The next chapter includes a vignette by Alissa Antle, elaborating on the Tangible Learning Design Framework.

Here, we review three content domains for learning in which TEI approaches have been widely adopted - moving from research labs into the wild. Our goal is not to provide a comprehensive review of TEI systems for learning, but instead, to demonstrate the application of such systems in various contexts and learning environments.

Programming and Robotics

TEI systems for programming and robotics have been used in formal and informal settings for more than four decades. In Chapter 1, we described one of the earliest tangible programming systems, the Slot Machine, which allowed young children to program the behavior of robotic "turtles." For an in-depth historical-technical survey of computationally-enhanced toolkits for children, we refer the reader to Blikstein's survey [Blikstein 2015], which examines design principles and provides a framework for the analysis and future design of these toolkits. In this section, we chose to highlight three TEI systems for programming and robotics that evolved from academic research projects into commercial products: the LilyPad Arduino [Education], Little Bits [littleBits], and KIBO [Robotics c]. These three commercially available toolkits were all created by women founders and share the goal of broadening participation in computing through creative engagement with STEAM (science, technology, engineering, art, and math).

The LilyPad Arduino is an open-source construction kit for e-textiles [Education], which was invented by Leah Buechley in 2006 during her Ph.D. work in Computer Science at the University of Colorado, Boulder. Leah created the LilyPad with the intention to broaden participation in computing and robotics by enabling less gender-biased projects through the integration of electronics and soft materials [Buechley et al. 2008b]. The commercial version of LilyPad [Education] was created through a collaboration with SparkFun Electronics and launched in 2007. The LilyPad Arduino kits (see Figure 2.1) combine sewable electronics with conductive materials (thread and fabric). Two years following its release, Bueckly and Hill investigated LilyPad's adoption 'in the wild' [Buechley and Hill 2010]. They collected and analyzed sales records and online project documentation and found that LilyPad was widely adopted by a new community of developers that differed in demographics from traditional electrical engineering and computer science developer communities. A significant percentage of the participants in this community were women. The projects built by the emerging LilyPad community were also different from traditional electronics and robotics projects and included interactive clothing, soft toys, costumes, sculptures, and sport accessories. The adoption of

Figure 2.1 Left clockwise: A biking jacket to signal turns; The LilyPad microcontroller kit with conductive thread; An interactive textile sculpture [Buechley and Hill 2010].

LilyPad 'in the wild' has broadened participation and motivated a growing body of TEI research focused on combining craft and interaction design [Buechley and Perner-Wilson 2012].

The littleBits physical electronics toolkit [littleBits] (see Figure 2.2) was launched as an open platform project in 2008 by Ayah Bdeir, an engineer and interactive artist, with the goal of enhancing creativity with electronics by "making prototyping with sophisticated electronics a matter of snapping small magnets together" [Bdeir 2009b]. The toolkit was released in 2011 as a commercial product. LittleBits consists of over 70 different color-coded blocks (pre-assembled circuit boards) that magnetically connect to each other by snapping together. The color codes indicate the category of the block: input, output, power, and logical operators. LittleBits' design is gender neutral and age agnostic. The bits are small and are easily combined with other materials such as paper, fabric, and cardboard. Most kits do not require a computer for programming the bits, however recent kits are accompanied by a dedicated mobile application. Educational materials are available for users and educators through mobile applications and online. LittleBits were evaluated 'in the wild' within various educational settings including schools, after-school programs, and workshops [Lin and Shaer 2016] and were shown to facilitate creative engagement and learning of computational thinking

Figure 2.2 Clockwise from top-left: Little Bits electronic toolkit; a robotic dog created by two kindergarteners; a cat project created by a third grader; and a bird project crafted by a fourth grader [Lin and Shaer 2016].

principles. Its wide acceptance and availability seem to successfully broaden participation in creative exploration with electronics.

KIBO is a robot kit (shown in Figure 2.3) designed for children aged 4-7 years old, allowing young children to build, program, decorate and "bring their own robot to life" [Robotics c]. The kit was developed by Marina Bers, at Tufts University, and became a commercial product in 2014. The current design of KIBO consists of a tangible programming language composed of different interlocking wooden blocks, and a hardware platform with a robotic body, motors, light output, a variety of sensors, and art platforms. Children build their KIBO robot by adding sensors and actuators to the body, and then program it by putting together a sequence of blocks (instructions). To run the program, they scan the blocks with the KIBO body and press a button.

This design is a result of an iterative process informed by research conducted by Bers and her students [Bers 2017]. KIBO's tangible programming language was inspired by the Tern system [Horn and Jacob 2007d] introduced by Michael Horn in 2007, who was co-advised by Rob Jacob and Bers, during his PhD studies at Tufts University. Bers and her team have developed new programming constructs, a novel implementation, an original robotics platform, and an innovative robotics curriculum. The KIBO robotic platform has been deployed along with its accompanying curriculum in schools around the world including the US, Argentina and Singapore, demonstrating that young children are able to learn core concepts of programming

Figure 2.3 KIBO robot, art platform and three programming blocks [Sullivan et al. 2015].

[Bers 2017] and can engage meaningfully with foundational concepts of engineering design [Sullivan et al. 2017].

Biology

Advances in life science technologies have transformed biological inquiry and have the potential to alter medicine to offer much-improved health care [Chin et al. 2011]. Biological technologies are also positioned to address pressing challenges, including food and clean water shortages, and increased demand for alternative energy sources [Carlson 2010]. Considering the transformative impact of biology, it is important to inspire the next generation of scientists and innovators to explore cutting-edge areas of life sciences including genomics, biological engineering, and synthetic biology. However, creating interactive learning activities in biology is challenging due to the several factors including the complexity of the topic, the long-time scales of living cells and organisms, prescriptive experimental design, and the fact that the behaviors of biological systems often occur at the nanometer level [Okerlund et al. 2016]. Based on our own experiences working at the intersection of biology and TEI both as interaction designers [Shaer et al. 2010, 2011, 2012; Ullmer 2012c; Wu et al. 2011] and genomic investigators [Han et al. 2007; Locke et al. 2011; Sequencing et al. 2007], we argue that TEI approaches offer unique opportunities for enhancing learning with biology. Here, we describe several projects, which make hands-on learning activities in biology accessible for K-12 students.

Orit Shaer (Wellesley College) collaborated with the Tech Interactive (San Jose, California) on the design of museum activities that engage young visitors in bio engineering and synthetic biology activities. These include Synflo [Okerlund et al. 2016] (shown in Figure 2.4), an exhibit designed to engage users in a simulated synthetic biology experiment through embodied

Figure 2.4 Left to right: Synflo study set up in a museum; users explore how to combine tangibles in Synflo version 3.2 [Okerlund et al. 2016].

Figure 2.5 Left: Children interacting with the BacPack for New Frontiers exhibit (photo courtesy of Ashley McCabe, Ashley Daubenmire Photography). Right top-to-bottom: Users select genes by placing tangibles on a DNA loop; Users drag custom designed DNA into bacteria petri dish; After custom designed bacteria multiply, user releases bacteria onto Mars [Loparev et al. 2016].

interaction, and BacPack for New Frontiers (shown in Figure 2.5), which invited visitors to utilize tangible block programming to design genetic programs which allow bacteria to consume resources on Mars to create products needed for astronauts to survive.

The TangiBac project, a collaborative National Science Foundation-funded project led by Shaer from Wellesley College and Bers from Tufts University, seeks to develop a suite of interactive tools and informal science curricula for K-6 students to explore foundational concepts of synthetic biology [Strawhacker et al. 2018]. The team adapted the exhibit BacPack for New Frontiers into a collaborative computer game for children in grades 3-6 taught in conjunction with a suite of educational videos and minigames. The team also developed CRISPEE (shown in Figure 2.6), a tangible, developmentally-appropriate tool to introduce

Figure 2.6 The current prototype of CRISPEE. Tangible blocks code red, green, and blue light to be either on (solid color) or off (colored line). Blocks are placed into the corresponding slots on the platform to create the genetic program of the firefly, with a colored output in the firefly's tail [Verish et al. 2018].

children grades K-2 to bioengineering. CRISPEE is modeled on the real-world CRISPR/Cas-9 gene editing system, and allows children to play with genetic programs to solve problems and explore the design and usage of "biosensors." The team deployed and evaluated CRISPEE in a series of science camps for young children conducted at Tufts Child DevTech Lab, as well as at bioengineering workshops conducted at the Boston Children's Museum. Their evaluation results showed that allowing children to explore biological engineering concepts in the context of a developmentally-appropriate tools and curriculum supported them in building initial ideas about engineering and life science through guided social interactions as well as to engage meaningfully with basic questions about the ethics of gene engineering.

TEI approaches also seek new ways to broaden access to biological data, materials, systems, and actual experimentation. DIYbio (Do It Yourself Biology) is an emerging movement [Kuznetsov et al. 2012] within the broader maker culture that seeks to enable designers and makers to experiment with biological protocols outside of traditional wet laboratory settings. In Arizona State University, Kuznetsov and her team converted an HCI studio into a biosafety level 1 laboratory facility through a process that included iterative development of low-cost tools, experimentation with (DIY)bio protocols, and the development of a bioart course for high school students to creatively paint with bacteria and antibiotic substances. Their findings from documenting and reflecting on this process "reveal the nuances of working with biological, analog, and digital materials in a design studio setting." [Kuznetsov 2018; Kuznetsov et al. 2018] Another system for hands-on experimentation with live microorganisms outside of traditional laboratory settings, My First Biolab (MFB) [Gome et al. 2019], was developed by researchers at the Interdisciplinary Center Herzliya, Israel. The system consists of a lab in a box with a novel disposable fluidic vessel, where experiments are conducted in a bag. MFB is affordable, safe, and sterile and supports temperature control, liquid circulation, measurement of optical density, and a web interface for remote control and monitoring. A different project - bioMAKERlab, is a wet laboratory starter kit for synthetic biology activities in high school classrooms, which was developed by Yasmin Kafai and her team at the University of Pennsylvania [Kafai et al. 2017]. This bio-fabrication tool supports microbial genetic modification and fabrication, providing students with a model for connecting biology with other making activities.

In Chapter 6, we expand the discussion on the intersection between TEI and biology by discussing TEI approaches, which provide new ways for enhancing exploration of biological data, and for designing with biological materials.

Cultural Heritage

Cultural heritage refers to the legacy of physical artifacts as well as intangible cultural traditions, expressions, and values, that are passed across generations [Ciolfi and Petrelli 2015]. The settings for sharing, displaying, or teaching cultural heritage vary from historic buildings, to museums, urban environments, and open-air sites [Ciolfi and Petrelli 2015]. Supporting and augmenting cultural heritage, is an established area within human-computer interaction. Ciolfi et al, provides a review of technologies and challenges for cultural heritage communities [Ciolfi et al. 2015].

TEI approaches have been particularly compelling for cultural heritage as they allow for materiality and authenticity that cannot be transferred through purely digital information. TEI design and technology enable augmentation through tangible artifacts, such as replicas, as well as transformation of indoor or outdoor surroundings into interactive spaces. Here, we describe three TEI installations that demonstrate how TEI approaches can engage learners not only with tangible cultural heritage assets but also with intangible values and traditions.

Reminisce [Ciolfi and McLoughlin 2017] is an interactive installation at Bunratty Folk Park, an open-air museum in Ireland that displays historic buildings and Irish ways of life from the past. The installation augments seven historic buildings with audio-based personal character narratives that visitors can explore through various devices and media, including a mobile application, an interactive desktop with tangible tokens, and a website. While navigating through the museum, participants can listen to and collect audio "memories" as well as contribute by recording their own memories. In the various buildings they also collect simple “mementos,” tangible tokens augmented with RFID tags. At the end of the tour visitors can share and access others’ memories using their tangible tokens and an interactive desk. Following the visit, an installation website allows visitors to revisit and reflect on their experience. The installation designers followed and adopted the “Assembly” design scheme proposed by Fraser et al. [Fraser et al. 2003], which emphasizes an interrelated activity narrative and information space for visitors to engage with while exploring an exhibition. An Assembly exhibit includes different forms of activities and content, and encourages active participation, rather than passive access to digital content. This approach is particularly appealing considering the heterogeneous and interconnected devices and technologies that have become increasingly available for museums and visitors.

The interactive Pen of the Cooper Hewitt Smithsonian Design Museum in New York City [Hewitt] (see Figure 2.7) allows visitors to actively engage with objects from the exhibit. Upon admission, visitors receive the Pen, which allows them to save and collect objects from the exhibit by pressing the flat end of the Pen to any museum label. Visitors can then transfer their collections to interactive tables available in the galleries, where they can further explore their collections, retrieve contextual information, learn more about designers, design processes and materials, and create and share their own designs. Visitors’ collections are also associated with a personal website (account information available on the admission ticket) where visitors can continue to engage with their collections. The Pen’s concept was created by the interaction design studio Local Projects working with studio Diller Scofidio + Renfro, envisioning a way to “invite visitors to learn about design by designing themselves” [Hewitt]. The deployment of the Pen has been widely successful, not only in engaging visitors while in the museum but also in facilitating return visits by visitors to their online collections [Dale].

Finally, ʔeləw̓kʷ – Belongings [Muntean et al. 2017] (shown in Figure 2.8) is an interactive tangible tabletop installation at the Museum of Anthropology at the University of British Columbia (UBC) which combines intangible cultural knowledge with high-fidelity replicas of belongings from an ancient Musqueam village site in modern-day Vancouver. This tabletop installation was designed through a participatory process to effectively communicate complex narrative information and values about Musqueam culture. The designers aimed to not only expose visitors to information, but also to help them experience Musqueam values through interactions with the system. In particular, the most important value the designers sought for visitors to experience was that "cultural knowledge should be treated with respect." Through an on-site evaluation, the designers demonstrated that tangible and embodied forms of interactions effectively facilitated an understanding of intangible values and heritage.

Figure 2.7 At the Cooper Hewitt, Smithsonian Design Museum, visitors receive a Pen to draw on interactive tables, save information to the pen and ultimately access a log of their museum visit online Museum, visitors receive a Pen to draw on interactive tables, save information to the pen and ultimately access a log of their museum visit online [photo courtesy of Orit Shaer].

Professor Eva Hornecker, Bauhaus-Universität Weimar
Tangible Interaction for Museums and Cultural Heritage

In science museums, tangible interaction has taken central stage already for decades in the form of hands-on interactives, that enable visitors to experience natural phenomena. With the democratization of museums and efforts to address new audiences and to make the visitor experience more playful and engaging, we see more and more tangible interaction also in other kinds of museums.

While hands-on interactives have proven popular, museum experts warn that these should go beyond handle-cranking and button-pushing, encouraging ‘minds-on’ learning [Allen 2004] – having visitors discuss, make and test hypotheses [Humphrey and Gutwill 2005], reflect about a topic, become creative, or contribute visitor-generated content

[Simon 2010]. While tangible interaction brings many advantages, as described below, designers of exhibits need to ensure they do not develop just another installation that diverts attention away from the actual contents of a heritage site or museum, or distract visitors from the overall setting and institutional aims.

Traditional museum technologies (audio guides or small-screen devices) tend to isolate visitors from each other, and interfere with natural group behaviors. Due to visibility both of interactions and objects, and the low threshold for interaction, tangible interaction supports group interaction [Hornecker and Stifter 2006]. Moreover, people can rely on well-trained coordination and conflict resolution mechanisms. Studies reveal that a tangible setup engages a more diverse audience than screen-based interactions, across ages and gender [Horn et al. 2009; Hornecker and Stifter 2006]. Horn compared a tangible puzzle-like setup versus a mouse-and-screen-screen version for programming a turtle-like robot in a science museum. Visitors were far more likely to try out the tangible version, to interact simultaneously with it, and children, in particular girls, had a more active role.

Tangible interaction can play diverse roles in museum and cultural heritage sites. The most common is to emulate a technical or scientific experiment or phenomenon, enabling visitors to go through the steps of an experiment or to rebuild a technical mechanism, with the digital augmentation system providing feedback and emulating phenomena. For example, Maquil et al. [2017] present an interactive workbench for discovering how batteries are built, that combines tangible interaction, augmented reality and embedded screens (see also Figure 1. Leuchtenburg). Tangible replicas can also be augmented to enable reflective multisensory experiences, for example, enabling visitors to hold a medieval prayer nut, to smell it, and to see how a believer would have entered the cathedral, with the visuals reacting to how the replica is held [Harley et al. 2016b]. Tangible programming environments [Horn et al. 2009] have also proven popular and effective in conveying basic algorithmic concepts to audiences in a playful way. Frequently, tangible objects are utilized in conjunction with interactive tables, where the tangibles provide easily understood entry points for interaction, and control a larger visual representation. Tangible objects can further be used for personalizing and guiding [Marshall et al. 2016] where visitors select objects (e.g. replicas) to choose a perspective to follow through a guided tour, while tagging the object enables the system to trace visitors' individual path and to personalize content.

Figure 1. At the Leuchtenburg Porcelain Experience exhibition, visitors enter a medieval alchemist's chamber where they can select and mix various ingredients, trying to recreate the correct constellation for porcelain. The scale dishes move up and down, giving indication of the correct ingredient relation, and flip over to empty their contents if the attempt goes wrong or visitors stop interacting. (Courtesy of Eva Hornecker)

Figure 2. Using tangible replicas (design: Nick Dulake) in the Atlantic Wall exhibition in Den Haag for personalized guidance. This exhibition was part of the EU project meSch.

Eva Hornecker is a Professor of Human-Computer Interaction at Bauhaus-Universität Weimar. Her research revolves around design and user experiences that go 'beyond the desktop' interaction, such as multi-touch surfaces, whole-body interaction and physically embedded computing. She proposed a unifying tangible interaction framework that helped establish the field of TEI research, and is one of the co-founders of the international Tangible, Embedded and Embodied Interaction (TEI) conferences. Understanding and designing for people's social interactions with and around tangible and embedded interfaces is a cornerstone of her research. Her recent work focuses on urban space installations.

Social Connectedness and Engagement

TEI systems for social connectedness help to maintain and enhance relationships with loved ones, friends, and caregivers, as well as to provide opportunities to engage in social activities and form new relationships. More broadly, Hassenzahl et al. identified 6 strategies that designers and researchers in HCI have applied to create a relatedness experience, including: awareness, expressivity, physicalness, gift giving, joint action, and memories [Hassenzahl et al. 2012]. Here, we consider three scenarios for enhancing connection and engagement using TEI: facilitating emotional communication between remote loved ones; increasing older adults' social connectedness; and improving engagement and socialization within families.

Figure 2.8 The ʔeləw̓kʷ – Belongings system consists of a Samsung SUR40 table, three monitors, twelve replicas, and two activator rings. Visitors are led through interactions that explore the identity, form, function, and connection between past and present for the belongings. Through exploration, users enact cultural values of respect and earn the right to uncover stories that reflect cultural narratives [Muntean et al. 2017].

Much TEI research investigates how to enhance emotional communication among remote loved ones by augmenting existing communication channels (see examples in Figure 2.9). Approaches range from interactive picture frames [Chang et al. 2001], to distributed play [Pan et al. 2017], location-based content delivery [Bentley et al. 2011], videochat and a shared tabletop task space [Yarosh et al. 2013], to transmitting touch [Seo et al. 2017; Singhal et al. 2017], kisses [Saadatian et al. 2014], and breath signals [Kim et al. 2015] using haptic and vibrotactile devices.

Several of these approaches have been applied ‘in the wild’ as commercial products that aim to enhance remote parent-child interaction or long-distance relationships. For example, Pillow Talk is a product designed by Joanna Montgomery to enhance long-distance relationships by transmitting one’s heartbeat to the pillow of their loved ones in real-time. Pillow Talk was successfully funded through a Kickstarter campaign, highlighting a desire for enhancing

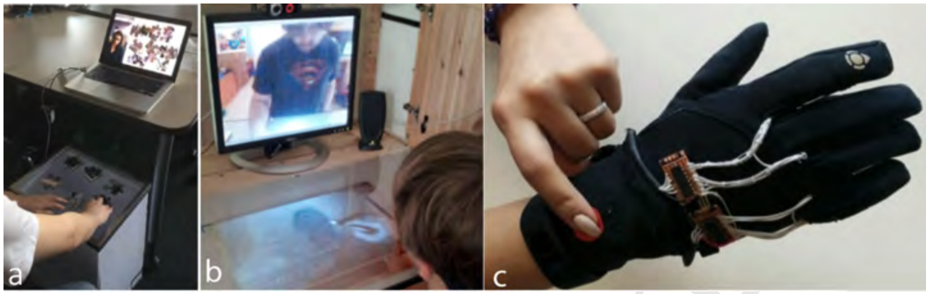

Figure 2.9 a) Puzzle Space allows long distance couples to solve a puzzle together with tangible and digital components (Photo Credit: Rui Pan); b) ShareTable allows for easy videochatting and an interactive tabletop task space to facilitate communication; c) Flex-N-Feel allows for a sense of touch for long distance couples (Photo Credit: Samarth Singal) [Pan et al. 2017; Singhal et al. 2017; Yarosh et al. 2013].

emotional connection across distance. TJacket [TWare] is a haptic vest that provides deep touch pressure, simulating the feeling of a hug. This system enables parents and caregivers to deliver calming touch and comfort remotely through an application. The jacket particularly targets children and individuals with sensory modulation difficulties, and is used in schools around the world.

TEI approaches are particularly appealing for increasing social connectedness and engagement of older adults because they can bridge traditional, familiar objects and novel technologies. TEI systems can be used to strengthen social ties between older adults and their families, and to encourage social engagement and new connections through shared experiences and through the exchange of stories and memories. For example, researchers explored the use of interactive textiles combined with an old-fashioned radio to allow older adults to connect and share experience by listening to old news and music [Nilsson et al. 2003]). Another project studied the installation of an interactive gallery and custom-designed camera kits as a means for increasing the social connection between older adults living in a care home and the surrounding local communities (see Figure 2.10) [Lin et al. 2016]. Both of these projects applied participatory design methods with older adults and were evaluated ‘in the wild’ through deployment in care homes. A wide variety of video and mobile applications have been designed to enhance communication between grandparents and grandchildren over distance [Neustaedter et al. 2015], however, the unique affordances of TEI approaches could be more appealing for both children and older adults. Family Story Play (see Figure 2.10) [Raffle et al. 2010], a collaborative research project between the MIT Media Lab, Nokia Research, and the Sesame Street Workshop, applied a TEI approach to support grandparents and grandchildren reading together over a distance. The interface combined a paper book, a sensor-enhanced frame, video con-

Figure 2.10 TEI approaches for increasing social connectedness and engagement of older adults. Top: Family Story Play [Raffle et al. 2010]; Bottom: ViewBricks [Lin et al. 2016].

ferencing technology, and video content of Elmo the Sesame Street Muppet. Evaluation with families demonstrated the potential of playful tangible approach to facilitate a creative shared activity over distance.

Interactive social companion robots, which embody artificial intelligence in mobile or stationary form, offer to aid and improve social connectedness for older adults and families, and are increasingly available ‘in the wild’ as commercial products. For example, ElliQ [Robotics b] is a stationary social robot designed to make it easy to connect with loved ones, support a variety of activities through reminders and online reservations, monitor and control smart home systems, and provide easy access to online information and digital content. Similarly, Buddy [Robotics a] is a mobile companion robot that provides similar functionality in a highly interactive and animated form, while Kuri [Robotics d] is a mobile home robot that was designed to support dynamic and playful interaction. Other robotic companions have pet-like embodiments and include products like PARO [Robots] the baby seal and Hasbro’s robotic cats and dogs [Hasbro]. These robotic pets look and feel realistic and provide companionship but do not require the care, time, and living conditions needed for live animals. Research indicates that robotic pets, and more generally, companion robots, provide positive experiences that increase social interactions and engagement in various audiences [Moyle et al. 2017a,b; Shishehgar et al. 2017]; however, more research is needed to understand the long-term impact of interactive companion robots on connectedness and engagement.

Health and Wellbeing

The rich physicality and variety of form factors of TEI approaches make them particularly compelling for health and wellbeing applications [Girouard et al. 2016]. For example, giving digital data a tangible embodied form and a physical method of control provides novel opportunities for interacting with data collected by sensors and tracking devices. Physicality also allows for customization and support of users with varying visual or motor abilities. TEI systems made of soft materials with rich textures can be used for cognitive assistant therapy, while peripheral interaction, where a tangible object can move in and out of a user's focus, can facilitate awareness and reflection. Indeed, TEI approaches have been applied to a variety of health and wellbeing use scenarios including rehabilitation, cognitive assistance, accessibility, and elderly care. Here, we focus on two application areas of health and wellbeing, highlighting TEI systems available 'in the wild' for enhancing awareness and monitoring, and for assistive technology.

Awareness and Monitoring

A wide variety of commercially-available TEI systems were designed to track health, exercise, or specific physical activity. For example, smart pillboxes such as Tricella [Inc.] or MedMinder [MedMinder] assist monitoring medication consumption of users with strict medication regimens, sending notifications to users or caregivers when one forgets to take their pills or accidentally takes the wrong medication. Smart water bottles such as Spring [Bellabeat] and Hidrate Spark [Hidrate] track and calculate the hydration one's body needs based on their physical activity and local weather.

TEI sleep tracking systems vary from wearable bracelets, watches, or rings to sensors that fit inside a pillow or under the mattress, to environmental sensors embedded in sculptural objects. Here we highlight a few examples of commercially available products. The Oura ring [Oura] is a sleep and activity tracker that measures motion, temperature, and heart rate, to present data about the different sleep stages. The screen-less ring was designed to be worn 24 hours a day and it provides data and insights in an accompanying mobile app. Other applications use the Apple Watch or iPhone sensors (required to place the phone near the pillow) to provide sleep data [Digital]. A wide variety of smart pillows are available on the market, which use embedded sensors for sleep tracking as well as provide additional features such as ventilation, sleep-inducing sounds played through private speakers, and alarm clock that is optimized based on the user's sleep cycle [Lacoma]. Sen.se's Mother and Cookies [Sen.se] is a commercially-

Figure 2.11 Left: Crimson Wave mirror glows different colors depending on user's state in menstrual cycle [Flemings et al. 2018]; Right: Leaf Urban wearable health tracker collects data on activity, sleep, meditation, stress and reproductive health [photo courtesy of Orit Shaer]

available system that applies a different approach for sleep and activity tracking. Rather than tracking a specific activity, the product consists of a collection of sensors that can be used to track a wide variety of activities. Sensors are placed by the user in or on different objects to monitor physical activity, usage, or state.

The design of these commercial products demonstrates that applying TEI approaches for tracking personal information on-the-body or in-the-home requires to carefully balance functionality, aesthetics, and materiality. While TEI systems for tracking personal information and monitoring physical activity are now common practice for millions of users [Fox and Duggan 2013], many of the existing systems fail to consider factors specific for women's health, including young adulthood, pregnancy, and menopause [Almeida et al. 2016; Balaam et al. 2017]. An important area for investigation is designing TEI system that are inclusive to people of different genders. One example of a TEI system designed for gender inclusiveness is Daysy, a fertility tracker that measures the user's body temperature to predict when they will ovulate and displays results through a light indicator and on a mobile application [AG]. Another example, still in the research phase, is Crimson Wave (see Figure2.11), a personal tangible user interface that generates and displays information about its user's menstrual cycle [Flemings et al. 2018]. The system consists of a mirror display and a wearable band for measuring basal temperature. Another example is the LEAF wearable health tracker (shown in Figure 2.11) [lea], which looks like jewelry and can be worn as a necklace, bracelet, pendant, or brooch (also shown in Figure 2.11).

Despite the wide variety and increasing availability of TEI systems for tracking personal information, more research is needed in order to understand the long-term impact of TEI tracking systems on health and wellbeing. It is also important to advance the body of knowledge

Figure 2.12 DataSpoon monitors movement kinematics during self-feeding for children with motor disorders [Zuckerman et al. 2016].

on designing for motivation and self-reflection, while considering not only the usage of a product but also its abandonment and the transition of usage from one tracking system to another [Epstein et al. 2016].

Assistive Technology

The unique characteristics of TEI systems, including rich physicality, spatial reconfigurability, persistence, and multisensory interaction, make them particularly suitable for applying universal and inclusive design philosophies, which can increase the usability and accessibility of technology for people with different physical and cognitive abilities and needs [Technology et al.].

People with impaired motor control and their caregivers might benefit from interaction with TEI systems that can detect and track movement kinematics as well as move automatically to support or complete a task. For example, Liftware [verily] is a commercially-available stabilizing handle for supporting self-feeding by people with hand tremor. It stabilizes the utensil by detecting and counteracting tremor - automatically moving in the opposite direction of a tremor. DataSpoon [Zuckerman et al. 2016] is a research project that investigates the use of a spoon instrumented with sensors for tracking the movement of children with motor disorders during self-feeding, in order to provide caregivers with precise assessments of their movement. The system was designed in close collaboration with caregivers.

When it comes to cognitive impairments, the use of tangibles for representing information in a physically persistent way, can potentially reduce the load on working memory and serve as a mnemonic aid for retrieving information from long-term memory [Technology et al.]. In addition, the perspective of embodied interaction treats physical engagement as an expression of the self, inviting the development of technology that supports creativity, engagement, and rich emotional expression while being attuned to subtle changes in gaze, facial expressions, and posture [Lazar et al. 2017]. However, despite the promise of supporting people with cognitive impairments, few such TEI systems have been developed and evaluated 'in the-wild.' Ly et al. [2016] introduced a prototype of a TEI system for reminiscing, which consists of a

Figure 2.13 Wobble is a prototype that explores using peripheral attention for long-term reminders [Zekveld et al. 2017].

chest of drawers. The system encourages people with dementia to reminisce through tangible interaction in the home environment. Wobble [Zekveld et al. 2017] (shown in Figure 2.13 left) is a prototype of a TEI system that explores how unobtrusive reminders for cued intentions are experienced in the home context. While designed for the general population, Wobble demonstrates the potential of creating memory cues that rely on peripheral interaction. A growing body of work in areas related to TEI systems explores the use of ubiquitous computing and augmented reality for supporting people with cognitive impairments in tasks at the home environment [Bouchard et al. 2006; Kosch et al. 2018; Miyawaki et al. 2009; Pollack 2005] and in the workplace [Chang et al. 2015; Funk et al. 2015; Kosch et al. 2016].

Professor Anne Marie Piper, Northwestern University

Supporting Older Adults with Dementia in Digital Social Sharing through Tangible Interaction

Sharing online is an important way in which people across the lifespan express themselves, maintain relationships, and connect with others. People with cognitive impairments, such as dementia, can experience challenges in understanding what it means to share information online as well as how to use traditional desktop or mobile interfaces. Over the last four years, we have conducted research within a memory care center for older adults. The majority of the adults we interacted with have dementia (e.g., from Alzheimer's disease, vascular dementia from stroke) that affects their memory, speech and language, and physical abilities (e.g., limited arm/hand mobility, use a wheelchair). Our work has focused on how these older adults' create, share, and connect through artwork created within an art therapy program. Art therapy is a mental health profession in which clients, facilitated by the art therapist, use art media, the creative process, and the resulting artwork to explore their feelings, reconcile emotional conflicts, foster self-awareness, and achieve other goals.

Despite the empowering experience of art therapy, many individuals with dementia are limited in their ability to share their artwork with others and benefit from the connections sharing may provide. Other people (e.g., therapists, family, staff) make many of the decisions regarding sharing, at times with little input from the individual with dementia. Additionally, none of the individuals we studied used computers or went online. In an effort to explore new technology-enriched interactions, our work and that of others has begun to examine the ways in which tangible and embodied interaction can support people with dementia. Physical props, for example, can support new forms of self-expression for older adults with dementia, in which holding or rearranging an object can indicate an individual's desires or constitute meaningful participation in an activity. Other artifacts, such as a microphone, are associated with the cultural practice of sharing one's voice with others.

To further understand how tangible interaction could support self-expression for people with dementia, we developed the Moments (Manipulating Our Material Environment To support Sharing) system. Moments is a wooden art frame with a tablet computer mounted inside and tactile buttons placed around the edges of the frame. Older adults with dementia, working alongside their art therapist, can capture images of their artwork and use the interactive physical buttons to record and replay audio to accompany the image. Additionally, the front-facing camera on the tablet scans the workspace in front of the frame and detects tagged physical objects and paper materials, which specifying with whom the work should be shared, if at all. For example, an older adult can share or gift artwork to others by placing tagged images of family members alongside the artwork. Placing a tagged paper envelope beside the artwork can send that work via email to a desired recipient. Other physical objects represent privacy settings, such as a treasure box or locket necklace indicating "just for myself" and a microphone for identifying content that can be shared more widely.

We found that the ability to position physical objects alongside digital materials helped indicate an older adult's desires for sharing and connecting with others. Revisiting audio recordings alongside the artwork and physical representations of an audience, which the user could touch, hold, and reposition, helped the therapist understand the older adults' preferences and intentions for sharing their work. The physicality of objects helped anchor conversation, and the layering and reorganization of objects provided persistent information about the meaning-making unfolding in the moment. While individual customization of the material workspace is essential, certain physical objects clearly signaled the concept of sharing, such as postcards, scrapbooks, framed artwork, and microphones. Future research can explore how other physical materials, such as tools for creating music or poetry, and our cultural practices using them, support new forms of interaction for people with dementia.

Anne Marie Piper is an Associate Professor at Northwestern University in Communication Studies. Her research in Human-Computer Interaction revolves around natural *user interfaces to support social interaction, learning and communication for people of all ages. She directs the Inclusive Technology Lab at NU, which primarily focuses on developing and researching new technologies for other adults and people with disabilities. Piper received a bachelor's in Computer Science from Georgia Tech, a master's in Education from Standford University and her PhD in Cognitive Sciences from University of California, San Diego.*

People with visual impairments could benefit from TEI systems that draw upon spatial encoding, use materials with rich tactile affordances, and provide haptic and audio cues. Such characteristics could support various areas of daily life including mobility, access to information, and education [Brock 2017]. However, relatively few TEI systems for people with impaired vision have been studied and deployed 'in the wild.' One example of a commercially-available wearable system for improving mobility is the Sunu band [Sunu], a sonar smartband that combines echolocation with gentle vibrotactile feedback to inform the user about objects or obstacles within their personal space. The band was designed to increase awareness and improve confidence for users, and is aimed to be worn in conjunction with the cane or guide dog. Another example, for an application which supports mobility, is the Microsoft Soundscape app [mic], which utilizes 3D audio to help people develop better perception of their surroundings. The application allows users to set audio beacons at their destination or familiar landmarks. As they walk, the application provides 3D audio hints, that are perceived as coming from the point of interest, helping the user to build a mental image of their surrounding – the soundscape. The application also calls out roads and landmarks as the user passes them. Similarly, to the Sunu band, Soundscape was designed to be used along other navigation support (other apps, guide dogs, or canes).

Several research prototypes explored how TEI approaches can improve access for information for people with visual impairments. For example, researchers at Texas A&M have developed STAAR (Situated Touch Audio Annotator And Reader) [Quek 2015], a system that provides spatial access to textual information. It consists of an e-reader application and an embossed overlay with a tactile pattern that allows users to move their finger across the text so that the system reads the text at the anticipated rate at which the user moves across the document. Markit and Talkit [Shi et al. 2017] (shown in Figure 2.14) is a toolkit for creating and interacting with 3D models that are augmented with audio annotations. Using the toolkit, makers can mark model elements and associate them with text annotations. A user with low vision can then print the augmented model, and use the Talkit application to access the annotations by touching the model. Other research prototypes provide people with visual impairments with access to graphs, diagrams and maps [Ducasse et al. 2016, 2018; Manshad et al. 2012; McGookin et al. 2010]. An example for a system deployed 'in the wild' is the Eone Bradley timepiece, a wristwatch that allows the user to tell time either through sight or through touch [eon]. The

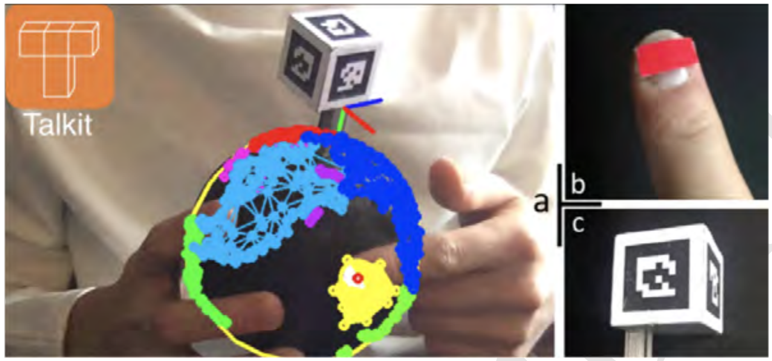

Figure 2.14 Top a-c: Markit and Talkit. Blind user 3D prints a modified globe. User places a sticker (b) on finger, and slides tracker onto the printed scaffold (c). User launches Talkit (a) application to hear audio annotations as she explores the interactive model; [Shi et al. 2017].

stylish watch has raised number markers and two ball bearings that indicate the current time in hours and minutes.

These examples demonstrate the potential and value of applying TEI approaches to empower users to access information previously inaccessible for them. While not yet available ‘in the wild’, the research prototypes provide useful guidance for developing non-visual tangible user interfaces. However, there is a need for additional research for understanding how to design and implement TEI systems that support visually-impaired people in a wide range of daily activities.

Summary

In this chapter, we surveyed examples of TEI systems, which have been deployed ’in the wild’ – in naturalistic real-world settings, and that aim to make a positive difference on individuals and communities. We showed, through these many examples, that applying TEI approaches to a wide range of application domains could increase opportunities for people from different backgrounds and with different physical and cognitive abilities, allowing them to participate more equally, actively, and meaningfully, in daily and social activities.

In the next chapters, we dive into the conceptual, cognitive, and technical facets of TEI, bringing together theory and practice.

3 Framing TEI

The first two chapters provided a broad overview of tangible and embodied interaction, laying the groundwork for a deeper investigation of four key facets: concept, cognition, design and technology, and aspirations. This chapter examines the evolving concept of tangible and embodied interaction (TEI).

Research efforts focusing on post-WIMP (Windows Icons Menus Pointing) interactions have developed in parallel in several institutions, resulting in the emergence of interaction styles and research areas that share a common vision with TEI - richer forms of human-computer interaction that interlink the physical and digital worlds.

For example, the vision of ubiquitous computing – profound interconnected technologies that disappear by "weaving themselves into the fabric of everyday life", introduced by Weiser [1991b] at Xerox PARC in 1991, has inspired numerous researchers and practitioners. In a 2004 paper titled "Bottles: A Transparent Interface as a Tribute to Mark Weiser", Hiroshi Ishii addressed a misinterpretation of the concept of ubiquitous computing, which focused on the "anything and anyplace computing" rather than on the transparency of technology and the user interface, and shared an inspiring personal communication with Mark Weiser that highlights a fruitful exchange of ideas. Weiser and Brown's concept of calm technology [Weiser and Brown 1996b] was developed in parallel with the Tangible Bits vision [Ishii and Ullmer 1997b] during the 90s, emphasizing the engagement of both the center and the periphery of our attention, and inspiring research on ambient displays. Another influential area is that of tangible augmented reality [Kato et al. 2001], particularly Wellner's DigitalDesk (1993), which used projection to augment tangible paper objects on a desk [Wellner 1993b]. These ideas have also inspired the research area of Interactive Surfaces and Spaces, which combines novel interaction techniques and emerging technologies.

We begin this chapter by surveying these research areas and their shared aspirations. We also consider theoretical frameworks that view TEI as part of an emerging generation of HCI, or of a larger interaction paradigm.

Finally, we highlight taxonomies and frameworks that forward the understanding of TEI by examining their properties, and provide conceptual power for analyzing and comparing TUI instances as well as generating ideas for new TEI systems. We conclude by discussing new directions that push the boundaries of TEI towards new paradigms and suggesting new areas for research.

Broader Research Context

Various conceptual and technological approaches have been influencing each other, resulting in an emerging generation of human-computer interaction styles that diverge from the traditional desktop paradigm and that provide new ways of physically interacting with digital information.

Ubiquitous Computing

Mark Weiser, then the director of the Computer Science Laboratory (CSL) at Xerox PARC, articulated his vision of ubiquitous computing in the seminal paper "The Computer for the 21st Century" [Weiser 1991b], published in Scientific American in 1991. Weiser envisioned a future where interconnected computational devices are integrated seamlessly into our everyday environment and play a prominent role in supporting daily work and leisure activities. Seamless integration also means that computing as a technology disappears into the background, allowing people to focus on their tasks and activities rather than on operating their devices.

In particular, Weiser describes how multiple computational devices of different sizes could be embedded in everyday artifacts and activities; for example, the foot-scale pad and the yard-scale board described by Weiser could support both individual and collaborative work, equivalent to today's tablets and large-scale displays. The inch-scale tabs described in the paper support a variety of tasks such as displaying state information as well as tracking location, activity, and objects. These devices are comparable to the Sifteo Blocks, which we described in Chapter 1, and to today's smart buttons, activity trackers, and watches.

Ubiquitous computing also involves mobility of both people and devices. Instead of only interacting with computers in a fixed location, people are capable of interacting with devices while in motion. Computing is pervasive, and some devices could be used everywhere.

Today, research in this area includes the design, implementation, and deployment of ubiquitous and pervasive computing technologies, as well as the study of human experiences and social impacts facilitated by these technologies [ubi 2017]. Also related to ubiquitous computing is the growth of the Internet of Things (IoT) [of Things Consortium] - a network of connected devices with services for a wide range of applications domains including smart homes, automotives, and cities. Numerous companies are providing IoT business solutions for a variety of industries ranging from retail, to healthcare, to manufacturing, to wildlife management. One distinction between Ubiquitous Computing and IoT is that while the IoT industry focuses on the development of new connected devices, infrastructure, and data collection and analysis methods, the research field of ubiquitous computing emphasizes human-computer and human-human interactions within a connected environment.

Tangible Augmented Reality

In a special issue of Communication of the ACM titled Back to the Real World, Wellner et al. [1993] defined computer-augmented environments as "... merge electronic systems into the physical world instead of attempting to replace them. Our everyday environment is an integral part of these systems; it continues to work as expected, but with new integrated computer functionality."

Around the same time, Augmented Reality (AR) technology, was defined more narrowly, aiming to seamlessly integrating digital information into the physical environment [Milgram and Kishino 1994]. However, rather than integrating computing devices and electronics in physical objects, AR focuses on presenting virtual objects or digital information alongside physical objects in the real world [Milgram and Kishino 1994]; the information can be projected upon surfaces or objects or displayed on a handheld or head-worn display.

Tangible Augmented Reality (Tangible AR) interfaces [Kato et al. 2001; Lee et al. 2004; White et al. 2009] are approaches which consistently with the early definition of computer-augmented environment [Wellner et al. 1993], combine tangible input with AR display or output. Imagine an environment where virtual objects or digital information are “attached” to physical objects - manipulating a physical object impacts the digital information displayed. For example, opening a book and flipping through its pages could impact the content presented on the book’s page. An early example of Tangible AR is Wellner’s influential Digital Desk [Wellner 1993b], a computer augmented environment for paper. The Digital Desk used projection to augment tangible paper objects on a physical desk, while computer vision tracked the location of physical objects as well as interactions with pens or fingers.

Later projects displayed 3D-visualizations of virtual objects overlaid onto physical objects. Implementation involved using computer vision to track visual markers and presenting the visualization on a display so that the imagery is shown at the same location and 3D orientation as the visual marker. Examples of this approach include augmented paper strips for air traffic control [Vinot et al. 2014], parallel web browsing [AlSada and Nakajima 2015], books [Billinghurst et al. 2001], entertainment [Zhou et al. 2004], and hybrid work environments [Gervais et al. 2016; Rekimoto and Saitoh 1999].

Advances in displays, spatial audio delivery, and tracking technologies (e.g. the Hololens [Microsoft] and MagicLeap [MagicLeap] devices) allow for blending digital content into the physical environment in new ways. However, virtual objects are easily distinguished from their physical counterparts upon touch due to the lack of haptic feedback [Vallino and Brown 1999]. Recent work in the area explores how to reduce this visual-haptic mismatch by scanning and selecting physical objects from the real environment that are similar to the virtual objects. Digital imageries could be overlaid on the selected physical objects to provide natural haptic feedback that matches the form of the virtual object [Hettiarachchi and Wigdor 2016].

Current research in this area focuses on improving user tracking, surface scanning, and display technology, as well as on enriching user experiences of interacting with tangible AR and mixed AR environments.

Interactive Surfaces and Spaces

Research on interactive surfaces and spaces focuses on interaction techniques and technologies for tracking user actions and objects upon a surface or within an interactive space. This area is inspired by and relates to both ubiquitous computing and AR.

Many tangible interfaces use interactive surfaces, often tabletops, with a tracking mechanism as the basis of interaction. For example, consider the Reactable system [Jordà et al. 2007b], which was introduced in Chapter 1. This system for digital music performers combines both tangible and multi-touch input upon an interactive tabletop.

Research within the area of interactive surfaces and spaces increasingly studies the use of mixed input technologies. Examples include integrating multi-touch and tangible input [Kirk et al. 2009]; utilizing active tokens with interactive surfaces [Valdes et al. 2014]; combining gaze and touch [Pfeuffer and Gellersen 2016]; and enhancing interaction with touch input on small screens with on skin-tap gestures [Zhang et al. 2016].

Researchers also explore flexible and shape-changing interactive surfaces [Ishii et al. 2012c; Vertegaal and Poupyrev 2008]. For example, Transform [Ishii et al. 2015b], which we discussed in Chapter 1, is a dynamic tangible display that transforms kinesthetically in response to the presence of physical objects, changes in data, and users' movements. Recent efforts also investigate the feasibility of interactive surfaces constructed with novel materials ranging from water condensation [Tsujimoto et al. 2016], to textiles [Poupyrev et al. 2016], to food [Zhang et al. 2016].

Ambient Displays

As part of the ubiquitous computing vision, Weiser and his team at Xerox PARC have developed the concept of Calm Technology [Weiser and Brown 1996b]. Calm technology was described as engaging both the center and the periphery of our attention while moving back and forth between the two.

Natalie Jeremijenko, then an artist-in-residence at Xerox PARC, designed an enchanting instrument for visualizing network traffic that demonstrates this concept. The LiveWire, or "Dangling String" [Weiser and Brown 1996b], was an eight-foot (2.4 m) string connected to a small electric motor mounted the ceiling. The motor was attached to an Ethernet cable. When the network was quiet the string twitched every few seconds; when the network was busy the string whirled wildly and produced a noise. The instrument was placed in a side corner of a workspace so that it is visible and audible from many offices, communicating information by taking advantage of peripheral cues.

Synergistically with the development of the concept of calm technology, Ishii and Ulmer included the use of ambient media for communicating information in their Tangible Bits vision [Ishii and Ullmer 1997b]. In particular, they described the use of media such as sound, light, airflow, and water movement in the periphery of human perception.

However, the concept of ambient displays soon developed into a research area of its own. Most ambient displays utilize purely graphical representations on screens of various scales, though multiple projects employ tangible interfaces as ambient displays. For example, Edge and Blackwell [2009] presented an interface consisting of tangible objects placed on a surface next to an office worker's workspace; this interface drifts between focus and periphery of a user's attention. The tangibles represent tasks and documents to support personal and group task management and coordination. Other projects investigated the use of tangible peripheral interaction for various contexts including augmented reality displays [Billinghurst et al. 2009], school settings [Bakker et al. 2015] and museum installations [Ullmer et al. 2017b]. Recent research has also explored the use of ambient notifications in smart homes environments, e.g. Wiehr et al. [2016], and the use programmable illumination [Takeuchi et al. 2016].

Unifying Frameworks for Post-WIMP Interactions

The above research areas focus on developing next generation human-computer interfaces that diverge from the traditional desktop paradigm. While they might seem to be disparate efforts advancing in different directions, it is important to consider their commonalities as a basis for understanding, connecting, and analyzing these interfaces. Following, we describe two unifying frameworks, which view post-WIMP interactions through a broader lens, allowing us to analyze and compare alternative designs while bridging gaps between tangible interfaces and seemingly unrelated research areas. Both frameworks can also guide us in creating new designs by encouraging designers to consider their choices against a set of principles, properties, and trade-offs.

Instrumental Interaction

Instrumental Interaction is an interaction model [Beaudouin-Lafon 2000] that extends the principles of direct manipulation to apply to post-WIMP interactions. The model is based on the observation that people naturally use tools (or instruments) to manipulate objects in the physical world. The model stresses that "our interaction with the physical world is governed by our use of tools," and thereby defines direct manipulation of objects as a process that occurs when people bring objects of interest into a particular context and manipulate them with suitable instruments. Such manipulation often involves two hands [Guiard 1987].

The model distinguishes between domain objects – objects of interest and the purpose of user interactions with a given application, and interaction instruments – artifacts that a user operates to manipulate domain objects. Users act upon an instrument, which transforms user actions into commands affecting the attributes of relevant target domain objects, and provides feedback as the command is carried out on target objects. The model also notes that an interface provides a potentially large number of instruments, but users might only be able to operate a small number of instruments at a time due to spatial or temporal constraints. In tangible and embodied interfaces both domain objects and instruments might be represented with physical objects. Many tangible and embodied interfaces can be described, analyzed, and compared in terms of domain objects and instruments, for example consider Urp [Underkoffler and Ishii 1999b], which we discuss in Chapter 1. Building models can be viewed as domain objects, which are operated upon using tools such as a material wand and clock. Metaphors based on tools or instruments have an important role in the design of tangible and embodied interfaces [Hurtienne and Israel 2007].

While reification is the process for turning concepts into objects, which can be represented explicitly and operated upon, Instrumental Interaction introduces a second type of reification: an interaction instrument is the reification of one or more commands. The model also highlights design trade-offs between temporal and spatial multiplexing of instruments along the dimensions of indirection, integration, and compatibility. Reasoning about reification while considering design trade-offs is important when generating and evaluating alternative designs of tangible and embodied interactions.

Reality-Based Interaction

The term Reality-Based Interaction (RBI) was proposed by Jacob et al. [2008] as a unifying framework that encompasses a large subset of emerging interaction styles including virtual reality, augmented reality, ubiquitous and pervasive computing, and tangible interaction. The framework views these emerging interaction styles as a new generation of human-computer interaction, referred to as reality-based interaction. This notion results from the observation that many of these interaction styles take advantage of users' experience and well-entrenched skills and allow interaction with the real non-digital world to a greater extent than traditional graphical user interfaces. These approaches offer fluid and free-form interactive experiences that are more similar to interactions with the real world, rather than being isolated from the non-digital environment.

The framework highlights four themes of interaction with the real world, which emerging interaction styles typically draw upon (see Figure 3.1):

- *Naive Physics* – the common-sense knowledge that people have about the real physical world.
- *Body Awareness and Skills* – people's awareness of their own physical bodies, and their skills of controlling and coordinating their bodies.
- *Environment Awareness and Skills* – people's sense of surroundings and their skills of navigating, manipulating, and altering their environment.
- *Social Awareness and Skills* – the awareness people have of others and their skills of interacting and cooperating with other people.

These four themes play a prominent role in the design of emerging interaction styles and provide a basis of human-computer interaction that is closer to interaction with the real, non-

Figure 3.1 The four RBI themes of interaction from Jacob et al. [2008].

digital world. Furthermore, the framework suggests that basing interaction on these preexisting skills and knowledge may lower the mental effort required to learn and to operate these systems and reduce the gulf of execution [Norman and Draper 1986], the gap between users' goals and the means to execute those goals.

The RBI framework encourages interaction designers to leverage reality-based skills and metaphors when designing interfaces. However, the framework also asserts that designers must still consider the trade-offs between reality-based interactions and other desired system qualities such as expressive power, efficiency, versatility, ergonomics, accessibility, and practicality.

In a paper published more than a decade after the publication of the RBI framework, Girouard et al. presented an evaluation of the RBI framework' impact on both contemporary research and HCI education [Girouard et al. 2019]. To assess the impact of the framework, they used mixed methods that include a citation content analysis and a survey conducted with HCI educators on emerging interaction frameworks. Their findings indicate that the RBI framework has remained relevant and in use despite the advancement of new technologies that could not have foreseen the authors when writing the original paper. The framework was widely adopted by researchers of emerging interaction styles and has been used to justify and explain the design of existing systems as well as to inspire new emerging lines of research.

Conceptualization of TEI

Historically, the name TEI stood for Tangible and Embedded Interaction [2], highlighting the technical notion of embedding computation in physical objects. This name was introduced in the call for papers for the first TEI conference, which was held at 2007 in Baton Rouge, Louisiana. We, the authors, have been involved in founding and leading this conference over the years, helping it to broaden its scope from technical to conceptual. This change was formalized in 2010, by changing the 'E' of TEI, to represent Embedded and Embodied interaction. In this book, we refer to TEI as Tangible and Embodied Interaction, highlighting the conceptual notions of the field while, in Chapter 4 we consider a wide range of technical methods for implementing TEI that go beyond embedded computation.

Following, we describe some of the frameworks which contributed to the conceptualization of tangible and embodied interaction. As this area matured, researchers have developed paradigms and frameworks for describing and defining the characteristics, qualities, and aspirations of the field. We chose to highlight particular frameworks; however, we acknowledge that other taxonomies and frameworks are also important as they emphasize additional aspects of tangible and embodied interaction. We encourage the readers to read Shaer and Hornecker's summary of conceptual frameworks and taxonomies for TEI [Shaer and Hornecker 2010a].

Early Work and Graspable User Interfaces

Inspired by Bishop's Marble Answering Machine [Polynor 1995b] and other predecessors of tangible interaction, which we described in Chapter 1, several research projects have explored the use of tangible or graspable media (i.e. tangibles). These early projects, developed in the mid- to late- 1990s, include work at Interval Research [Cohen et al. 1999b; Singer et al. 1999b; Withgott 2015b], Hinckley's "passive real-world interface props" at the University of Virginia [Hinckley et al. 1994b], Suzuki and Kato's "tangible programming languages" at NEC [Suzuki and Kato 1993], and Fitzmaurice et al. [1995b] work at the University of Toronto, which developed the concept of "graspable interfaces."

Graspable user interfaces [Fitzmaurice et al. 1995b] were defined as providing a "physical handle to a virtual function where the physical handle serves as a dedicated functional manipulator." Users have "concurrent access to multiple, specialized input devices that can serve as dedicated physical interface widgets." An important property of these input devices is their affordance of physical manipulation and spatial arrangement.

Fitzmaurice et al [Fitzmaurice et al. 1995b; Fitzmaurice 1996] describe the following core characteristics of graspable interfaces:

- *Space-multiplexing* – input devices can be classified as being space-multiplexed or time-multiplexed. When only one input device is available (e.g. a mouse), it is necessarily time-multiplexed — the user must repeatedly select and then deselect objects and functions. By offering multiple input devices, so that input and output are distributed over space, graspable user interfaces allow for simultaneous, independent, and potentially persistent selection of objects. Therefore, space-multiplexing allows for concurrent access and manipulation with two hands or by multiple users.
- *Specific input devices* – the use of input or output devices with rich affordances that are dedicated to a specific functionality and potentially embody that functionality.
- *Spatial awareness and reconfigurability* – the use of physical input devices is inherently spatial. Input devices can be arranged and rearranged spatially in a way that is also physically persistent. This allows users to leverage spatial awareness and reasoning as well as muscle memory.

By describing these properties, Fitzmaurice et al. provided an early definition of a novel design space, and helped to highlight opportunities for further research.

Tangible Bits and the MCRit Interaction Model

Drawing on these early investigations, as well as on new research at MIT, Ishii and Ullmer articulated and demonstrated the concept of tangible interfaces. Their Tangible Bits vision [Ishii and Ullmer 1997b] aims to "bridge the gaps between both cyberspace and the physical environment, as well as the foreground and background of human activities." In particular, they identified three key concepts for making digital information available through the physical environment:

1. *Interactive Surfaces* – transforming surfaces within architectural space (e.g., walls, desktops, ceilings, doors, windows) into human-computer interfaces;
2. *Coupling of Bits and Atoms* – augmenting everyday graspable objects (e.g., cards, books, models) with related digital information;
3. *Ambient Media* – using ambient media such as sound, light, airflow, and water movement to communicate information through the periphery of human perception.

In 2001, following the design and development of additional TUI instances, Ullmer and Ishii presented first steps toward characterizing tangible user interfaces as a distinct and cohesive research area [Ullmer and Ishii 2001]. They defined tangible user interfaces as systems that "give physical form to digital information, employing physical artifacts both as

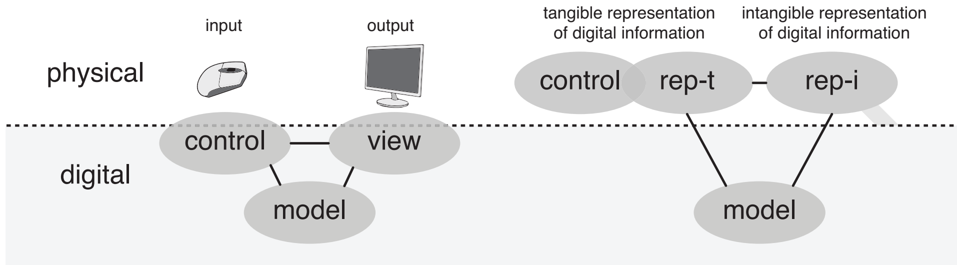

Figure 3.2 Comparing the MVC (left) and MCRit (right) models (redrawn based on Ullmer and Ishii [2001]).

representations and controls for computational media," and presented an interaction model and key characteristics for such tangible user interfaces.

Drawing from the MVC (Model-View-Controller) model of traditional graphical user interfaces, Ullmer and Ishii proposed the MCRit model (Model-Control-Representation intangible and tangible). While the MVC model separates the view (i.e. graphical representation) and the controller, which is mediated by input devices (i.e. a mouse and a keyboard), the MCRit model integrates physical representations and control, thereby eliminating the distinction between input and output devices. The "seamless integration of representation and control" implies that tangible objects embody the means for both representing and manipulating digital information. Figure 3.2 illustrates the MCRit model.

Ullmer and Ishii also identified three major approaches for interpretation in tangible user interfaces: spatial, relational, and constructive [Ullmer and Ishii 2000b].

In spatial systems, the underlying system tracks, interprets, and augments the configuration of physical tokens within one or more physical reference frames. Consider the URP interface [Underkoffler and Ishii 1999b], described in Chapter 1. It can be viewed as a spatial system, since the spatial configuration of the physical tokens is interpreted in respect to the interaction surface.

In relational systems, relationships between physical tokens such as sequences, adjacencies, and other logical relationships are interpreted and mapped onto more abstract computational interpretations. This approach opens possibilities for rich physical syntax. For example, recall the Slot Machine of Perlman, an interface for controlling LOGO's robotic and screen-based "Turtle," which we described in Chapter 1 [Perlman 1976b]. In this interface, multiple cards could be stacked upon one another to create composite commands. For example, a number card could be stacked upon an action card to indicate move forward a certain number of steps. Finally, in constructive systems, the assembly of modular elements is sensed and interpreted through mechanical connections (e.g. in a fashion similar to LEGOTM bricks). For instance, both the Building Block System (BBS) [Aish and Noakes 1984b] and the Universal Constructor [Frazer et al. 1980b], which we review in Chapter 1, consist of modular systems of physical blocks, mediated by technology.

These classifications of spatial, relational, and constructive systems are not mutually exclusive; instead, they highlight promising spaces for design at the intersection between two or more approaches.

The definition, interaction model, and preliminary classification of tangible user interfaces provided by Ullmer and Ishii have been revisited and expanded upon by the numerous researchers working in the area of TEI.

Tokens and Constraints

Continuing to explore the design space of tangible user interfaces, Ullmer et al. [2005b] articulated and illustrated a new approach for tangible interaction with digital information. Their Token+Constraint approach combines tokens and constraints, two kinds of physical/digital objects. Tokens represent digital information, while constraints provide structure (e.g. stacks, slots, racks), which guides users how to (and how not to) manipulate and compose tokens onto various computational interpretations. Figure 3.3 illustrates configurations of tokens and constraints. This approach has been applied mostly in the design of TUIs with abstract digital information that has no inherent tangible representation or physical manipulation syntax. For example, Ullmer et al. [2003b] illustrated this approach in their Tangible Query systems. The Marble Answering Machine [Polynor 1995b] and the Slot Machine of Perlman [1976b] are also typical examples of this approach.

In parallel, Shaer et al. introduced the TAC (Tokens and Constraints) paradigm [Shaer et al. 2004b]. This framework provides a set of constructs and a high-level method for describing the structure and functionality of a broad range of TUIs, helping designers to analyze and compare past examples, as well as to design and consider interactions for a new system. Shaer and Jacob also used the TAC paradigm as the basis for a high-level description language, TUIML, and a software toolkit for TUI development [Shaer and Jacob 2009]. They demonstrated how the high-level set of abstractions provided by the framework can be used to specify key and diverse examples from the TUI design space.

Embedded Interaction

Kranz, Holleis, and Schmidt proposed the term embedded interaction to describe the technological and conceptual phenomena of augmenting everyday artifacts with means for human-computer interaction [Kranz et al. 2010]. This perspective highlights technical aspects of embedding sensing, actuation, processing and networking, into everyday objects, as well as conceptual facets of embedding interaction into users' everyday tasks. They identified the Internet of Things, as a key enabling factor for implementing the vision of an ecology of augmented and connected objects that constitutes a virtual overlay on the physical world. This perspective

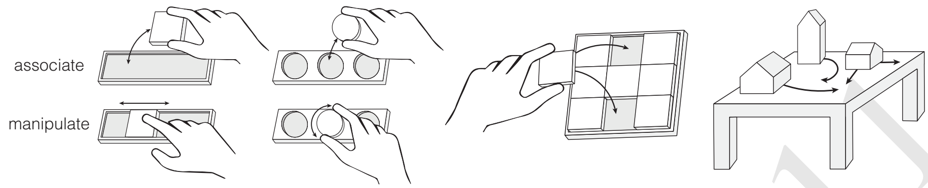

Figure 3.3 Tokens and constraints – tokens represent digital information, while constraints provide structure, serve as a frame of reference, and guide the users how to manipulate tokens. Tokens and constraints can be combined to provide a physical syntax of interaction through association and manipulation. (redrawn based on Ullmer et al. [2005b] and Shaer et al. [2004b]).

has a different focus from that of tangible bits because it is focused on augmenting exiting objects rather than on designing novel tangible representations. However, they acknowledge that adding functionality without changing the way an object originally behaves or looks, might introduce new challenges. More specifically, they describe the invisibility dilemma – hiding computational augmentation yet at the same time communicating to users which objects are augmented. The framework also highlights the notions of explicit vs. implicit interaction, where explicit interactions means that the user operates a system knowingly and implicit interactions are caused by the user engaging in a daily activity that involves augmented objects and spaces (e.g. entering a room, using a pen).

The framework of embedded interaction provides design and technical considerations for researchers and practitioners who develop new systems. The conceptual notion of embedding interaction into users' everyday tasks and context is further examined and discussed through the perspective of Embodied Interfaces.

Embodied Interfaces

The rise of embedded interaction, which augments everyday artifacts and the physical environment with computing, created a need for considering new human computer interactions – ones that are situated in social, cultural, and physical contexts. In his 2001 book, "Where the Action Is — The foundations of Embodied Interaction" [Dourish 2001a], Dourish used the term embodied interaction as "interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with...

Professor Yvonne Rogers, University College London
Tangibility and Embodiment: Moving Beyond Grasping

a) A pair of children using our tangible toolkit Magic Cubes - to learn about coding, IoT and electronics. b) The physical-digital fish pond at Great Ormond Street Hospital. c) Answering questions using physical sliders when interacting with VoxBox. (photo courtesy Yvonne Rogers)

Much has been written about the benefits of tangible and embodied interaction, where physical objects and surfaces are overlaid with digital representations, and where grasping the physical form causes a change to the associated digital information. Since their inception, the concepts of tangibility and embodiment have been extended in a variety of ways leading to new design possibilities. This suggests that in the future we begin framing them more as design principles, rather than as properties per se, that can inform creativity in design. Below, I describe three examples of how we have been inspired to think differently; from objects to surfaces to surveys.

1. *Physical-digital objects* can be held in our hands and manipulated in various ways. Cubes, spheres, toys, rods, balls, bricks, phones and other customized artefacts can be interacted with, by themselves, or with other surfaces, causing digital content to appear and move on, around and nearby – be it shadows, shapes, graphs, creatures, plants and the like. This way of engaging with technology can appear to be quite magical; encouraging individuals to explore, discover and want to learn more about different cause-effects. They can also trigger social interactions, such as spontaneous collaboration. For example, we have found in our research that children often want to show and tell others about their achievements when using one of our tangible toolkits [Johnson et al. 2016].
2. *Physical-digital surfaces* can elicit a variety of embodied interactions. We can use our bodies to make digital content stir, through moving around on floor displays and in front of wall displays. An example is an animated digital fish pond that is projected on the floor of the reception area at Great Ormond Street Hospital in the UK. It is programmed to move virtual fish around in response to someone standing on it by changing their direction as if moving away from the person. As part of an ethnographic study, we observed it being used by many families who

were visiting; it was highly accessible and anxiety-reducing, drawing children of all ages and physical (dis)abilities and, occasionally, some adults to use it [Lim et al. 2019]. It was also seen to facilitate creative use. For example, children experimented with different parts of their bodies to make the fish react. Parents were seen helping their physically disabled or wheelbound children try interacting in the space through improvising with their restricted movement. The interactive surface was also able to elicit a diversity of subtle and explicit interactions where others nearby, joined in; watching, commenting or talking with the acting child, while sitting in the same area.

3. *Tangible Surveys* – We can think of tangibility in terms of how it changes the way we interact with technology. For example, we developed VoxBox as an innovative method for gathering opinions and gauging the mood of communities or crowds at events [Golsteijn et al. 2015]. Responses were made physically by touching it rather than filling out a form on paper or a website. In particular, people answer questions by using a range of sliders, dials and knobs. As well as gathering opinions, VoxBox allows people to see how their views compare to those of other people, by looking at digital visualisations that appear in realtime. It was also designed to be colourful, physical and playful in appearance, in order to grab people's attention and invite them to come and touch it. We have found that in many contexts, this kind of touchable interface has been highly successful at encouraging a diversity of people to participate to give their opinions. The physical actions of moving sliders and turning physical dials – instead of clicking on checkboxes or putting a cross on a scale – appears to put people into 'the zone'; as if physically feeling what it is like to respond to each question.

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...us." (p.3) This definition, which emphasize embodiment as situatedness in physical, social, and cultural contexts, became a popular term within the HCI community.

Antle further emphasized that embodied interaction involves understanding "how the nature of a living entity's cognition is shaped by the form of its physical manifestation in the world" [Antle 2009], viewing users' bodies, their movement in the space, and their physical interactions with objects, as key aspects of embodied interaction designs. Klemmer et al. [2006]

presented themes for designing and evaluating tangible and embodied interfaces including, thinking through doing – deep integration of mind and action when learning and reasoning; performance – rich, effective, and nuanced actions that human bodies are capable of; and visibility - artifacts as mediators for collaboration and cooperation.

These perspectives on embodied interaction are strongly influenced by ideas from philosophy and cognition. Specifically, they draw on the phenomenological paradigm, which emphasizes the role of physical actions, perception, and experience of 'being in the world' in meaning making, as well as on theories of external, situated, and distribution cognition, which view cognition as a process that integrates our brain, our body, and our social and physical environment. In the next chapter, we review theses theoretical foundations in depth and discuss their implications for the design of TEI systems.

Since tangible user interfaces seek to 'give physical form to digital information' thereby making computing part of the everyday physical world, the concepts of tangible and embodied interactions are highly interrelated, and can be viewed as complementary. Tangible computing emphasizes physicality, representation, form, materiality, and tactile interaction, while embodied interaction highlights the role bodily actions within physical and social contexts on shaping and augmenting cognition. In the next section, we review the Tangible Interaction design framework [Hornecker and Buur 2006b], which highlights common themes for tangible and embodied interfaces.

Tangible Interaction

In 2006, Hornecker and Buur [2006b] proposed the term Tangible Interaction, which expands Ullmer and Ishii's definition of tangible user interfaces [Ullmer and Ishii 2001] in order to describe a broad range of tangible and embodied approaches originating in different disciplines. Their Tangible Interaction framework connects and relates systems that use tangible representations to support the manipulation of digital and physical elements, while also enabling rich or skilled bodily interaction.

As an encompassing perspective, this framework emphasizes four interrelated themes:

- *Tangible manipulation* – the material representations, their distinct tactile qualities, and the physical means for interaction.
- *Spacial interaction* – the embodiment of tangible interaction in real space and interaction, and interaction through movement and action in a physical space.
- *Embodied Facilitation* – the configuration of material objects and space and their impact on emerging group behavior.
- *Expressive representation* – the material and digital representations, their expressiveness, and their legibility.

By highlighting these four themes, the framework provides a lens that aids in the comparison and analysis of existing systems, as well as in the design of new interfaces through deliberate and careful consideration of alternative designs.

vignette : Prof. Eva Hornecker, Bauhaus-Universität Weimar
Using Theory in a playful way for Design and Evaluation: the TEI framework cards

In HCI, we love to have theory. But its very nature can be in the way for making theory fruitful for design. This starts with how much you need to read to fully understand. And when have you understood well enough? Applying theory in design then is top-down, which can result in great principled designs, but also stifles creativity. The common approach of distilling design guidelines from theory does not really resolve this.

When developing my TEI framework, discussions with designers and design educators unearthed another concern: For designers, guidelines are there to be understood and then to be broken with intent, not to be used as a checklist. Many designers just dislike them. Moreover, guidelines and checklist can result in thoughtless adherence, they do not guarantee good design. Thus, instead of guidelines, the TEI framework has sensitizing questions at its lowest, concrete level. We felt this to be particularly appropriate since not every aspect of the framework would be important for any given application or setting to design for.

Taking inspiration from design game approaches read about and experienced, we wanted to let people work directly at the level of sensitizing questions in a way that enables creative and playful exploration of ideas. The card set was developed over several iterations of refining questions phrasing and accompanying inspiring images, tested in design or evaluation sessions with groups previously unfamiliar with the framework. For a design exercise, the cards are mixed and handed out. Then, the design team can take turns suggesting a card (and question) as being relevant and start to discuss ideas, or as being unimportant or even as something to be purposefully negated. An interesting observation from the sessions I facilitated myself is that these ‘discarded’ cards often generate just as much (fruitful) discussions and ideas as the ones chosen as relevant. The cards being paper scraps invites playful behavior and flexible interactions, mixing them, tossing them about, shoving around, piling and distributing, even crushing them.

Figure: Taking turns, each team member can suggest a card. The team then discusses and decides if the card is applicable or not, which can then inspire new ideas or be used to evaluate a design. At the end, chosen cards remain on the table. Color-coding of cards serves as implicit reminder of themes or to determine at glance which theme ended up most important for a design task.

The card exercise was published at TEI (Hornecker 2010) and the card set can be downloaded from my website to be printed out and cut to size. Occasionally, I hear from academics teaching tangible interface design who like to use the cards for ideation, or for evaluating designs and prototypes, where they help to invoke good conversations while encouraging participants to refer back to the theory behind them.

The card-game approach as a more playful, creative way of engaging with theory and for turning conceptual frameworks and sets of design criteria into an inspiration for design has become even more popular since. Various other card-games have been developed to support ideation in specialized areas of design. Some intend to make complex theory accessible to designers, e.g. a card set on children's age-specific developmental abilities regarding cognitive, physical, social, and emotional abilities (Bekker and Antle 2011) or the Tango cards which inform design of tangible learning games (Deng, Antle and Neustaedter 2014). Others address areas related to tangibles, such as the design of exertion games (i.e. embodied interaction) (Mueller, et al 2014) or designing for the internet of things (Angelini et al 2018, Mora et al 2017).

Figure: 4 example cards (visual design, thanks to Elisabeth Eichhorn)

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Extending the Playfield of TEI: Pushing Boundaries and Changing Paradigms

Expanding the Scope of Materials and Tangibility

"Our goal is to invent new design media for artistic expression as well as for scientific analysis, taking advantage of the richness of human senses and skills we develop throughout our lifetime interacting with the physical world, as well as the computational reflection enabled by real-time sensing and digital feedback." - Hiroshi Ishii [Liberty]

The role of materiality in interaction design is increasingly embraced as a "broader view of a practice of imagining and designing interaction through material manifestation [Wiberg 2018]." In his book on the Materiality of Interaction, Wiberg proposes to adopt and apply material-centered interaction design. This approach resonates and elaborates the discussion of a CHI 2012 panel titled "Material Interactions – From Atoms and Bits to Entangled Practices", where participants highlighted "a move away from a perspective that treats people and computers as two separate and distinct entities toward a perspective that acknowledges how people, computational materials, and even traditionally non-computational materials are coming together as a whole [Wiberg et al. 2012]."

This is an exciting time for considering the materiality of TEI. The materials TEI is playing with is changing – the physical and dynamic qualities of materials are getting less rigid and mechanical. Developments in this area encompass new materials with applications in shape-changing interaction, novel and flexible materials, multi-sensory interaction, wearables and smart fabrics, and data physicalization [Jansen et al. 2015b].

Radical Atoms

Inspired by advances in material science, nanotechnology, and self-organizing micro-robotic technology, Ishii et al. articulated the vision of Radical Atoms [Ishii et al. 2012c], which explores novel interactions with dynamic materials. Radical Atoms refer to interactions with physical materials that "can transform their shape, conform to constraints, and inform the users of their affordances." Ishii et al. explored and illustrated this approach through design exercises and prototypes built with current and emerging technology.

Radical Atoms interfaces exhibit one or more of the following characteristics:

Figure 3.4 Transform – dynamic furniture that senses kinetic energy and transforms it into dynamic movement [Ishii et al. 2015b].

- *Direct touch and gestural interaction* – to allow users to explore dynamic materials in varying scales, radical atoms interfaces combine low precision, wide-ranging gestural interaction with high precision, fixed-scale touch interaction.
- *Dynamic affordances* – the affordances of dynamic materials change as the interface's shape alters. Thus, the user has to be continuously informed about the function the interface can perform in its current state.
- *Context-aware transformations* – radical atoms interfaces sense information such as identity, grip, and environment conditions to infer context. Interfaces then transform to a shape and configuration identified as the best solution for a particular context.
- *Shape memory* – interfaces can be pre-programmed to 3D primary forms. Users can conform the interface material to constraints of primary 3D forms by approximating them and then letting them "snap" into the closest pre-programmed shape.

For example, consider the interface Transform [Ishii et al. 2015b], which we introduced in Chapter 1. Transform is a dynamic furniture that consists of three shape displays. It senses the kinetic energy of viewers (i.e. gestures), and transforms it into dynamic movement that can be pre-programmed to simulate a broad range of material properties (e.g. stiffness, elasticity, viscosity). Users can also interact with the interface through direct touch and through the placement of static physical objects upon the interface. Figure 3.4 illustrates the functionality and aesthetics of Transform.

Figure 3.5 Programmable Droplets uses droplets of liquids to change the shape of food [Umapathi et al. 2018].

Additional examples include Programmable Droplets [Umapathi et al. 2018] (shown in Figure 3.5), a water-based interface that uses droplets of liquid for information manipulation and human interaction. The system utilizes the technique of “electrowetting on dielectric” (EWOD), which enables to program operations such as translating, morphing, merging, and splitting multiple droplets in parallel; and Transformative Appetite [Wang et al. 2017b] (see Figure 3.6), a project that explores the use of edible 2D films made of common food materials (protein, cellulose or starch), which can transform into 3D food during cooking. A transformation is triggered by water adsorption. Users can design and customize food shape transformations through a pre-defined simulation platform, and then fabricate these designed patterns using additive manufacturing.

The characteristics of Radical Atoms open numerous questions for designing interactions with dynamic materials, allowing designers to expand upon and explore new forms of tangible and embodied interactions.

Ephemeral User Interfaces

TEI researchers have explored the use of ephemeral materials such as ice, soap bubbles, and smoke – designing multisensory interfaces where parts of the interface intentionally disappear or degrade over time [Döring et al. 2013b]. A project funded by the German Research Foundation investigated the design space of ephemeral interfaces [Döring et al. 2013a] and outlined their characteristics.

Examples include TastyFloats [Vi et al. 2017] (shown in Figure3.7), developed by the SCHI Lab at Sussex University, a taste delivery system that uses acoustic levitation to deliver food morsels to users’ tongue as well as the Soap Bubble Interface [Sylvester et al. 2010], which uses

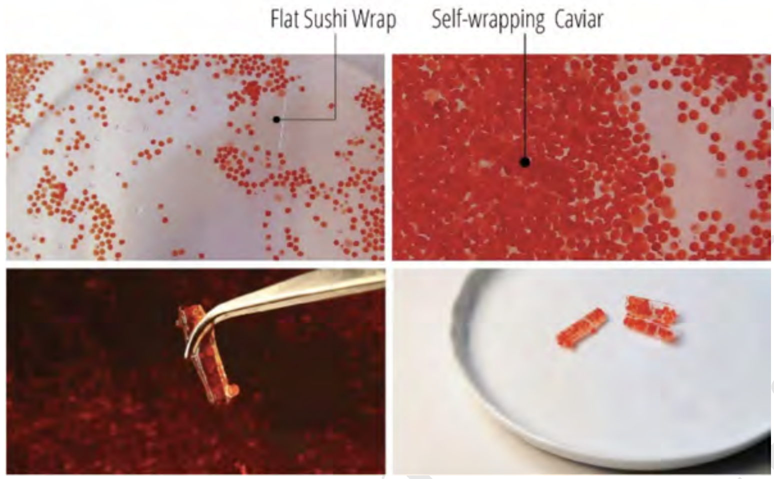

Figure 3.6 Transformative Appetite explores food that changes shape through interaction with water, for example, self-wrapping water sushi [Wang et al. 2017b].

smoke-filled soap bubbles that float on a liquid surface to control sounds and room light. Users interact with the bubbles - moving them on the surface by waving, blowing or gently touching the bubbles. When the user destroys a bubble, a handle to control sound and light is gone but new soap bubbles can be generated. Figure 3.8 shows interaction with the Soap Bubble interface. Researchers from Finland presented a design space for ice as a design material reviewing examples and domains of using ice as part of interactive systems [Colley et al. 2018; Virolainen et al. 2010]. For example, figure 3.9 shows an interactive ice slide embedded with LEDs.

The design space of ephemeral user interfaces (see Figure **??**) provides opportunities for future work including the development of multisensory programmable ephemeral materials, new tools for developing such interfaces, and novel metaphors and frameworks [Döring et al. 2013a].

Shape Changing Interaction

Other materials and interfaces leverage reconfigurability and shape changing. Shape changing interfaces consist of objects that can be either deformed manually by a user through direct interaction or automatically actuated to change their shape.

For example, kinetiX is an auxetic-inspired material structures that transform upon compression [Ou et al.] shown in Figure 3.10. Auxetics are structures or materials that have a negative Poisson's ratio. When stretched, they become thicker perpendicular to the applied

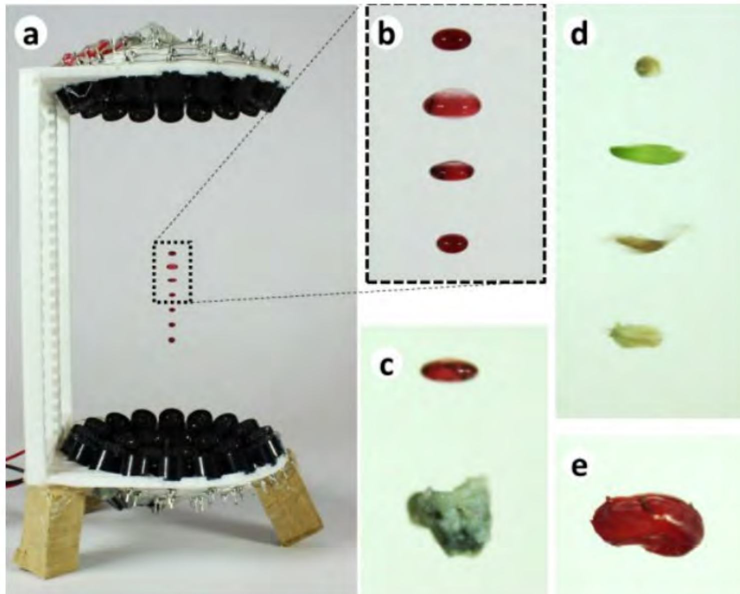

Figure 3.7 TastyFloats uses acoustic levitation to transport food into the user's mouth. a, b) Acoustic levitation of droplets of wine; c) Wine and blue cheese; d)Bread, lettuce, meat and bread; e) and a raspberry grain [Vi et al. 2017].

Figure 3.8 The Soap Bubble Interface makes users interact with fragile bubbles to interact with the computer. A user moves a smoke-filled soap bubble in order to influence the room illumination [Sylvester et al. 2010].

force [aux]. The system consists of cellular-based material structure units composed of rigid plates and elastic/rotary hinges, which can be combined to create different transformations.

An example of shape-changing interaction in our everyday homes is the Ripple Thermostat [van Oosterhout et al. 2018b] (shown in Figure 3.11), which is a tangible interface that combines haptic feedback and shape-change to convey affective information towards its users. The bi-directional communication between thermostat and users can support concepts such as negotiation between temperature settings or provide information through its appearance or response. This project illustrates the rich and expressive power of interacting with an intelligent

Figure 3.9 Interactive wall made of ice [Virolainen et al. 2010].

Figure 3.10 A 1D tessellation of spatial transformation of bending and twisting. This tessellation creates a curling strip [Ou et al.].

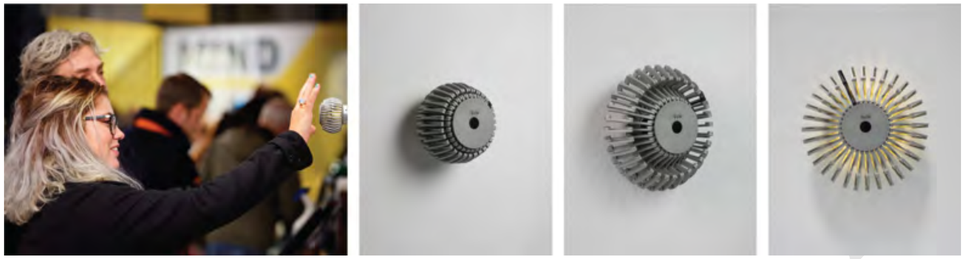

Figure 3.11 The Ripple Thermostat combines haptic feedback and shape-change to negotiate about the temperature settings and provide information about the temperature through its appearance or response [van Oosterhout et al. 2018b] (Left photo: Bart van Overbeeke, other 3 photos: Anke van Oosterhout).

system through tactile modalities. In particular it highlights the opportunities for designing the behavior of systems that change their tactile properties over time and through interaction.

Shape changing interfaces surface can be developed at various scales. The architecture and design magazine Dezeen has a special feature on buildings adjusting their shape based on the contextual conditions or the kind of interaction [Carter 2017]. The Hyperbody group, founded and directed by Prof. Kas Oosterhuis at the Delft University of Technology, researches and develops computationally-driven interactive architecture, which is parametrically actuated by users and their immediate environment. Their architecture is based on complexity theories, especially swarm theory, i.e. the space is formed and informed by smart interacting parts which act like birds in a swarm. In addition to developing new prototypes of architecture, the group also creates tools and methods needed for designing and constructing this new type of interactive building [Oosterhuis 2012]. Figure 3.12 shows examples of shape changing architecture.

Several emerging shape-changing interface taxonomies [Kim et al. 2018; Rasmussen et al. 2012; Roudaut et al. 2013; Troiano et al. 2014] aim to describe the reconfigurability of interfaces. These taxonomies map the design space of shape changing and reconfigurable interfaces and can be used to inform the design new interfaces.

Micro, Meso and Macro Scales

When looking at the TEI systems described in the first two chapters, one can see that most examples are at the micro scale of interaction - small-scale setting of an individual or a group of users interacting within their direct environment.

However, we see a need for design and development on a meso scale (the medium-scale setting at the level of a community or region) and even at the macro level (the larger cultural and societal scale) to address our societal challenges. At the meso scale new platforms were

Figure 3.12 Left: One Ocean Pavilion, designed by Soma Architecture [som] and created for the South Korea's Expo in 2012, has a kinetic facade with slats that open and close individually to create a rippling effect (photo Soma Architecture). Middle: The Hyperbody group develops prototypes to explore the possibilities of computationally driven interactive architecture based on swarm theory. The large panels can move based on external conditions forming a movable wall (Photo by Festo AG). Right: The Hyperbody group creates also shape-shaping interior and furniture (Photo taken by Hyperbody TU Delft).

developed for crowd-computer interaction [Brown et al. 2009], interactive audience participation [Ludvigsen and Veerasawmy 2010; Maynes-Aminzade et al. 2002], and public displays [Claes and Moere 2015; Müller et al. 2010]. At the macro scale, virtual communities on social networking platforms like Facebook, LinkedIn, Twitter, and Instagram provide a platform for connection.

The last few years have seem new developments at the cross-section of TEI and the Internet of Things, which are referred to as the Internet of Tangible Things [Angelini et al. 2018a; Gallacher 2016] (IoTT) or Internet of Tangibles [Angelini et al. 2018b]. IoT has the potential to also enable interactions at a meso or macro scale, although the interactions can also focus on or be perceived by users at a micro level.

Drawing upon previous work on embedded interaction [] and sensor-based interaction [Bellotti et al. 2002b]. Angelini et al. [2018a] examines eight tangible interaction properties which can be used for designing novel interactions with IoT objects:

- Meaningful representations and controls of the single IoT object connectivity status and IoT object interconnections, as well as of information capturing, elaboration and sharing.
- Rich interactions that exploit natural human skills, in particular exploiting haptic and peripheral interactions with IoT objects that are situated in the physical world.

- Persistent physical representations that could last in case of power or connectivity outrage, allowing the user to control the state of an IoT object even when no Internet connection is available.
- Spatial interactions that support collaborative setups with multiple IoT objects.
- Immediacy and intuitiveness of the interaction, facilitating the understanding and control of IoT objects with minimal learning time.
- Interactions with IoT objects that are integrated in daily routines, which free users' cognitive resources and do not disrupt attention.
- Facilitated reflections on IoT object meaning and working principles, as well as support for associating and sharing memories.
- Long-lasting interactions with IoT objects, exploiting emotional durable designs to cope with electronic waste due to technological obsolescence.

This list offers help to move IoT in the direction of IoTT, and expand TEI towards the interconnected world of tangible objects. The focus of IoTT is on the tangible and embodied character of the objects and the quality of interaction with these objects. However, this framework does not offer specific support when exploring the connections between the people interacting via these objects, potentially at a meso or even macro scale.

Several recent projects have begun to examine such connections from a TEI perspective: Stoffel Kuenen [Kuenen 2015] presented the notion of aesthetics of being together in his PhD thesis, where he explored how the presence of others is expressed in the presence of an artifact (and vice versa). For example, his group-mediating system Sliders consists of a number of networked linear actuators (motorfaders) that enable a group of people to feel each other remotely [Kuenen 2015]. Bogers et al. [2017] explored how multiple people can be connected using TEI, focusing on the qualities of that interaction. For example, their Wearable Team Coach project (see Figure 3.13) consists of connected basketball jerseys and bracelets that measure ball contact, and display this contact via five light stripes on the jerseys. The participants in the user studies indicated that the jerseys affected their choices during the game and made them more conscious of the social aspects of the gameplay [Bogers et al. 2017]. Although these designs are still tested on a micro scale, they have the potential to move towards a meso scale.

Over the past decade, Marianne Graves Petersen and Peter Krogh conducted research on new forms of computer mediated ways of social engagement of co-located people within the Center for Interactive Spaces, such as the iFloor, an interactive floor based on the architectural archetype of a well that creates a space for people to gather and interact [Krogh et al. 2004], and Hydroscope (shown in Figure 3.14), which stimulates curiosity, collaboration, and embodied learning in children through peephole experiences [Dalsgaard et al. 2008; Dindler et al. 2007]. The studio Tangible Interaction [Interaction], founded by Alex Beim, has created dozens of

Figure 3.13 The Wearable Team Coach aims at going beyond micro scale interaction, by helping players to experience the social relationships in their team via feedback and feedforward in their jerseys and bracelets [Bogers et al. 2017] (photo Sander Bogers).

sensory installations that connect large groups of people in playful and poetic ways. Their installations use tangible and embodied interaction to enable dozens of people interacting in public spaces and at events. Related initiatives are explored by Interactive Spaces Urban Studio [Studio], who created public interactive installations such as PIXLdance, which is an interactive sound and light installation. Their Interactive Bench installation plays audio fragments of the lives of the people living in the area.

While these examples show some of the possibilities of TEI approaches for meso and macro scale interactions, the full potential of TEI on a meso and macro scale is still in its infancy and requires extensive research. The potential roles of different modalities for large group interactions, such as audio, touch, and smell, are still underexposed. When talking about the meso and macro level, one touches immediately upon scalability. The level of scalability of TEI is generally limited in comparison the digital world. These larger scales of interaction and the need to "design tangible systems with simplified scalability" [Wallbaum et al. 2017], present opportunities for new TEI paradigms that go beyond the micro level of individual or small group interaction to explore TEI at the community and societal levels.

Summary

As the area of TEI has evolved, researchers have proposed numerous frameworks and taxonomies that provide different perspectives on the design space. Most frameworks provide researchers with explanatory power, enabling them to reason about, classify, analyze, and compare interfaces. Some frameworks provide generative capacity as well, highlighting open opportunities in the design space and informing the design of new interfaces.

Figure 3.14 Hydroscope: this Peephole experience allows users to look down into the digital ocean through the hydroscope, and encourages active exploration through pushing the hydroscope around the floor to reveal more of the ocean (photo courtesy Christian Dindler). [Dindler et al. 2007]

Mazalek and Hoven proposed to map the framework space for TEI to help designers identify which frameworks could guide them based on their needs [Mazalek and Van den hoven 2009]. They created a two-dimensional framework map where the vertical axis represents the facet of tangible interaction addressed by the framework - technologies, interactions, physicality, domains, and experiences- and the horizontal axis represents the type of frameworks - abstracting, designing, and building. Within this space, frameworks are denoted in a type/facet area using boxes. As there are numerous frameworks that we could not include in this chapter, we encourage the reader to revisit Mazalek and Hoven's original frame work map [Mazalek and Van den hoven 2009].

In the next chapter, we look into the philosophical and cognitive developments that inspired and informed the conceptualization of TEI.

4 Theories of Embodiment

The previous chapter described the evolving notion of TEI and the various perspectives that together make up the conceptual foundations of this field. In this chapter we delve into the cognition facet that influenced and informed the concept of tangible and embodied interaction. In particular, we focus on the notions of cognition that recognize that we are physical beings, and that our existence is grounded in the physical world and is processed through our sensory and motor interactions with the space around us and with the things and people that exist within it.

Although this may seem obvious and relates to longstanding ideas that are at the core of the philosophical movement of phenomenology [Moran 2000], the broad shift from a centralist (brain-centric) view of cognition to what Killeen and Glenberg [2010] call an "exocentric paradigm" represents a "sea change" that is still rolling out in the cognitive sciences [Hostetter and Alibali 2008]. We draw on this evolving view here, understanding cognition as a process that happens not in the brain alone (with perceptual and motor systems acting as mere inputs and outputs for thoughts happening in the head), but rather as a process that engages the brain, the body, and the physical and social environment together. This paradigm is supported by a wide array of empirical evidence as well as differing but related research approaches that have been characterized broadly by terms like "embodied cognition," "situated cognition," and "distributed cognition" [Hutchins 1995; Kirshner and Whitson 1997; Shapiro 2011], and will be discussed in some more detail in this chapter.

Introduction

We opened Chapter 1 by noting the transformative power of the digital medium, which now seems to touch nearly every aspect of human engagement. Drawing on Murray [2011], this transformative power is driven by the encyclopedic, procedural, participatory and spatial affordances of the digital medium, which serve as the designer's palette for creating digital representations and experiences. The digital medium can store and access vast amounts of information in different formats; modify and create information based on computational processes; invite human action and manipulation of represented information; and provide navigable remote or virtually constructed spaces. These affordances have been key in expanding the scope of what we can accomplish with digital technology for work and leisure alike, from e-commerce and social media platforms, to scientific visualization and computer games.

Yet, the screen-based computer interfaces that dominated our digital experiences for decades created a gap between our digital experiences and our in-the-world physical experiences. Just as the cognitive sciences are navigating a "sea change" to a more embodied view of cognition, so too is the field of HCI shifting from predominantly screen-based forms to more tangible and embodied experiences of digital information. And as these two shifts operate in parallel, HCI researchers and designers can and must look to embodied cognition as a framework for digital, tangible and embodied interaction design. Per Kirsh [2013], "HCI is at a crossroads. We are entering a new world of physical, natural, and tangible interfaces. We can interact with digital elements by gesturing and body movement, by manipulating everyday objects, and even by training brain activity to control interfaces. To understand the design principles of such a world requires that we become familiar with the ongoing developments in embodied, distributed, and situated cognition, and build closer relations to their research agenda." (p.26)

Thinking with Things

Before digging into relevant past and ongoing developments in embodied cognition and related areas, we look at some examples across four areas: discovery and learning, design and making, storytelling and memory, and social play. These areas are not intended to provide a comprehensive framework of thinking with things, but rather aim to serve as a structure within which to explore some relevant historical as well as contemporary examples that can provide some insight and inspiration for how we think, play and connect with each other through bodily engagement with, and material manipulation of, physical artifacts.

Discovery and Learning

First designed and built in the early 18th century, the Orrery mentioned in Chapter 1 is a mechanical device that both calculates and represents the passage of planets (see Figure 4.1, left). In his book *Thing Knowledge* [2004], Baird discusses the Orrery at some length, explaining how it embodies knowledge through its material relations, both geometric and causal. These material relations produce a demonstration, powering the model's ability to explain and predict. Baird also discusses another prominent example, the double helix model of DNA built by Watson and Crick (see Figure 4.1, right). Built from the geometric relations of physical balls and sticks, this model enabled the two scientists to quickly form and test out hypotheses about the structure of DNA by manipulating the model's physical structure.

Both the Orrery and the DNA model serve as examples of how artifacts embody knowledge, specifically what Baird [2004] calls "model knowledge". Model knowledge highlights the epistemic status of models, providing entry points for cognition in the form of both conceptual and material manipulation. The tactile manipulation, which can be structural but might also be chemical, thermal, electrical, or other, is especially critical in cases where conceptual manipulations may be too difficult due to analytical complexity or lack of theory. As Baird writes about James Ferguson's 1744 Orrery and Watson and Crick's DNA model, "Ferguson was able to find the moon's orbit [around the sun] with his material model when an analytical

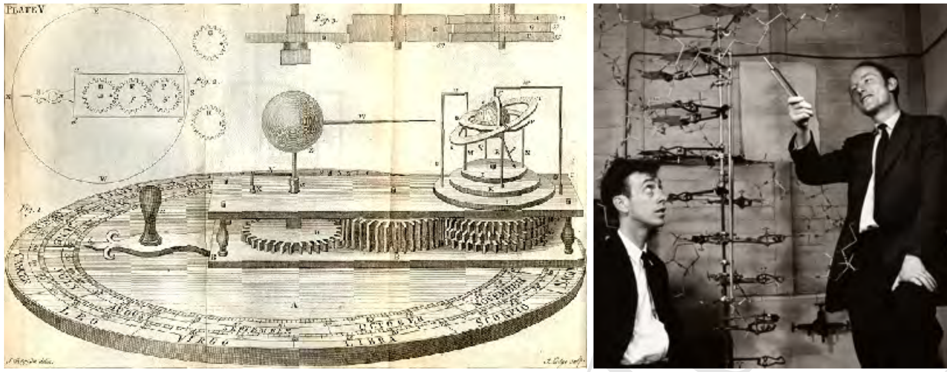

Figure 4.1 Illustration of **wooden pulley Orrery** by James Ferguson, c. 1755 (left). The orrery was used to illustrate the motions of the Moon and Earth around the Sun. **DNA model** by Watson and Crick, 1953 (right) [A. Barrington Brown/Science Source]. Watson and Crick used a modular physical model to build and test the structure of DNA.

approach would have exceeded the computational abilities available to him. Watson discovered pair bonding through the manipulation of material objects – cardboard cutout models of the bases – in space when an analytic approach would have taken too long, if, indeed, it would have succeeded at all.” (p.39)

Recent work in TEI has highlighted the opportunity to link physical models to computational ones, which can extend their scope to areas that involve large and complex data sets, and to dynamic systems that may lack an inherent spatial structure. One example of this is the Active Pathways system [Mehta et al. 2016a], in which users manipulate active tangible blocks on a tabletop surface in order to construct models of biochemical reaction networks (see Figure 4.2, left). Creating a reaction between two molecules in the network is as easy as touching together two blocks that represent the corresponding molecules. The mathematical equation that describes this reaction is then generated in the background, and equation parameters such as molecule concentrations can later be adjusted using the same blocks as physical dials. Users can also simulate the model, as well as load experimental datasets and test the model against, with results visualized dynamically on the tabletop display. Through physical manipulations, users can thus build up an understanding of the behavior of the system they are modeling.

Baird also describes other ways that artifacts, specifically scientific instruments, embody knowledge. He calls these “working knowledge” and “encapsulated knowledge.” Working knowledge describes the way certain artifacts constitute knowledge by creating phenomena, for example the devices Michael Faraday built in 1821 to produce electromagnetic rotation. Encapsulated knowledge describes how certain artifacts like those used for measurement combine both model knowledge (since a model must be built into the artifact) and working knowledge (as the artifact itself has to present a phenomenon given the appropriate inputs or

Figure 4.2 **Active Pathways** [Mehta et al. 2016a] uses active tangibles on a tabletop surface to model biochemical reaction networks and test the built models against experimental datasets (left). **Tern programming blocks** [Horn and Jacob 2007a] use the physical manipulation of interlocking blocks to represent actions for a robot to perform (right).

manipulations). A classic TEI example, the abacus [Ishii and Ullmer 1997b], encapsulates a numerical system and presents the results of calculations such as addition and multiplication through the material manipulation of its components. What is particularly interesting about the abacus is the way it works as a cognitive support when people perform calculations, its physical pieces serving as both a material mode of representation and control. Research on gesture and mental representations has shown that when people who have been trained to use a physical abacus are asked to do "mental abacus" (abacus-like calculations in their head), they gesture in a way that reflects the movements used to operate the physical abacus. Interestingly, people perform significantly worse in these mental calculations when their gestures are inhibited [Brooks et al. 2018]. Clearly, the motor system, with actions guided by a physical artifact, is heavily involved in their cognitive performance.

Our understanding of the way children learn also shows the importance of interaction with physical artifacts and materials. Martin and Schwartz [2005] have investigated how actions impact thinking and learning, suggesting that the way in which this happens depends both on how stable the child's ideas are and how stable the environment they are working within is. Having stable ideas and working within a stable environment allows the learner to off-load their thinking into the environment. When the learner's ideas are not stable, a stable environment that offers strong constraints and clear feedback can guide interpretation. When the learner's ideas are stable but their environment is adaptable, this can leave room for the learner to develop their own problem-solving strategies. And lastly, if both their ideas and the environment are adaptable, a learner may interact with the environment without knowing exactly what steps to take or even what they want to achieve. In studying how children learn fractions with different materials, Martin and Schwartz [2005] found that a benefit of physical actions for learning abstract ideas is that it allows new interpretations to emerge through physical adaptations to the environment. This relates to constructivist and constructionist theories of learning of Piaget [1952] and Papert (see e.g., [Papert and Harel 1991]), which view knowledge as something that is actively constructed by children in their interactions with the world. These theories underlie pedagogies such as the Montessori method [Montessori 1912], which encourage hands-on exploration and bodily engagement with physical artifacts. In the TEI context, researchers have integrated these approaches with computation, for example as we discussed in Chapter 2, to introduce children to programming concepts through physical manipulation of interlocking blocks that represent actions for a robot to perform [Horn and Jacob 2007a] (see Figure 4.2, right).

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The Tangible Learning Design Framework: Setting an Agenda for Tangible Learning

In the early years of tangible computing, as is typical of a newly emerging field, much research and development was exploratory and speculative in nature. I saw an opportunity to turn the field's attention to a more systematic and theory-driven approach to designing tangibles, specifically for learning. The Tangible Learning Design Framework [Antle and Wise 2013b] contributes to this agenda in three ways. First, we created a taxonomy that highlights different elements of TUI design that are important to consider in learning contexts either because they present unique opportunities to support learning interactions or because they relate to critical elements of learning that the design of any TUI with learning as a goal should take into account. Second, taking a pragmatic approach to epistemology, we analyzed multiple theories of cognition and learning and extracted explicit mechanisms that we thought lend themselves to being augmented by the unique features of tangibles. Based on this analysis, we derived actionable guidelines, where evidence existed, stated at a level of specificity that allowed designers to use them not simply as a justification for why TUIs should be used in learning but to inform specific design choices. Lastly, by laying out the connections between TUI design choices and cognitive and learning theories, we proposed testable explanations about how and why TUI design was expected to impact learning and raised research questions where guidance was lacking.

There were two areas where our framework deeply guided our own subsequent investigations of tangible learning systems. First, the theory of epistemic actions taken from embodied cognition was instrumental in our exploration of the benefits of tangibles in supporting young children at-risk for dyslexia in learning to read. Epistemic actions are a strategy whereby part of a mental task or operation is dynamically distributed to action in the environment and those actions are used to change the world in some way that makes the task easier to solve. Although we did not design to explicitly support epistemic actions, since this area was under explored in HCI, the theory provided a lens in our analysis of children's hands-on actions with our tangible reading system, PhonoBlocks. What became readily apparent were the design choices we had made that then enabled children to simplify the task of learning to spell by using epistemic strategies (see [Fan et al. 2016, 2017b] for details). A contribution of this work is evidence for how and why epistemic actions support learning to read and spell with tangible letters.

Second, we used the theory of positive interdependence in collaborative learning, to explicitly design a tangible tabletop called Youtopia [Antle et al. 2013b]. Youtopia is a collaborative land-use planning system that enabled us to explore how to design to collaborative learning that contained instances of rich negotiation and reflection. We designed Youtopia following our own guidance to distribute tangible controls across social roles (land use developer or resource manager) using codependent access points (creating land-uses required sequences of actions with physical tools which distributed across roles). In detailed coding of video data we found evidence that most children collaborated throughout their sessions, addressing concerns of competitive interaction in tabletop environments [Wise et al. 2015a, 2017]. More importantly, we found evidence of rich dialogue around the role values play in decision making, and productive instances of negotiation and conflict resolution – all of which are critical to learning about value-laden subjects.

In summary, our framework continues to provide guidance for exploratory design work as well as a blueprint for research questions and hypotheses that can be used to generate empirical support for the proposed benefits of tangibles systems for learning.

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Design and Making

Beyond learning and discovery, physical models serve as 'tools to think with' in other kinds of creative processes, such as architecture and design. Models built during the design process enable architects and designers to explore different ideas, and to progressively revise and refine them in a tangible way and at increasing levels of detail [Dunn 2010]. Like in scientific discovery, hands-on model-making fuels creative inspiration through material manipulation,

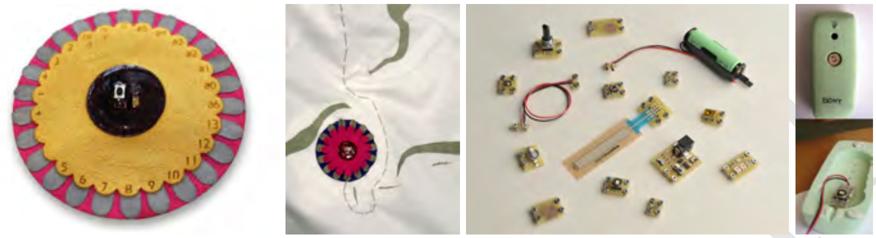

Figure 4.3 **Lilypad Arduino** [Buechley et al. 2008a], a fabric-based construction kit for e-textiles, shown here embellishing a sweatshirt with an LED whose color changes in response to arm gestures (left two images). **littleBits** [Bdeir 2009a], pre-assembled board components that can be combined with analog materials for electronics prototyping, as in this example of a homemade back-lit remote control (right two images).

and yields a deeper understanding of the built structure. Dunn [2007] describes different types of models used in the architectural design process, including descriptive models (like those used to illustrate and communicate ideas in a presentation), evaluative models (which seek to provide a qualitative understanding of a proposed reality though their use), predictive models (which aim to produce quantitative data through their use), and explorative models (which are used as tools for engaging with design questions such as space and form). Although nowadays much of the architectural modeling process happens digitally, architects often still turn their virtual models into physical ones via 3D printing or laser cutting, and many still use physical model-making by hand to help shape, visualize and evolve their ideas. Renowned architect Frank Gehry, for example, uses explorative model-making extensively throughout his design process , and it is only in the later stages of his design process that his practice turns to computers [Dunn 2007].

Assembling and repurposing materials is also an important part of the tradition of craft and DIY (do-it-yourself) creative practices. People engage in craft and DIY activities for many different reasons, such as the desire to customize things they own, the desire to learn new things, or simply a personal creative drive. Over the past decades, emerging interaction technologies have extended DIY design and making practices to include digital and electronic materials, often in combination with physical materials such as textiles, wood, paper and paint. A variety of toolkits have to support these activities, and some of these have been picked up and even fueled by the HCI and TEI community. In Chapter 2, we described the the LilyPad Arduino [Buechley et al. 2008a] - a fabric-based construction kit for e-textiles, and littleBits [Bdeir 2009a] - an opensource library of pre-assembled circuit boards for electronics prototyping, are examples of toolkits that aim to support creative making practices that combine digital electronics with traditional analog materials (see Figure 4.3).

Storytelling and Memory

The above examples all show how external artifacts act as a key part of scientific reasoning and design processes, but we can just as well look to cultural artifacts throughout history to see how they embody memory and stories. The Lukasa (see Figure 4.4, left) of the Luba peoples of central Africa, mentioned in Chapter 1, provides a striking example of how beautifully crafted artifacts can capture both shared and personal histories through tangible and spatially encoded elements (such as beads and carvings) that represent place, genealogy, political relations and more, in a way that is not static but rather open to interpretation. Roberts and Roberts [1996a] call the performance with a Lukasa a "generative reconstruction of the past" (p.118); as the performer's hands run across the surface of the Lukasa, the artifact serves as a kind of performative mnemonic, triggering memory during the act of storytelling. And this storytelling performance, with the Lukasa as well as with other Luba artifacts such as beaded necklaces, headdresses, staffs, spears and scepters, is an inherently social process, bringing community members together in the co-construction of memory. As Roberts and Roberts write, "Mnemonic devices elicit visual, verbal, and performative arts, and Luba objects were and are read, spoken, sung, danced, and manipulated." (p.44). In recent work, the concept of the Lukasa was re-created as a tangible tabletop installation piece (see Figure 4.4, right) that was shown as part of the Mapping Place exhibit at the Robert C. Williams Paper Museum in Atlanta, GA [Chu et al. 2015b]. At the exhibition, an authentic Lukasa resided inside a glass case, leaving visitors to shape their understanding of the artifact and its rich physical and embodied meaning based on their visual sense alone, by examining the artifact at a distance and reading the accompanying textual descriptions. In contrast, the interactive installation provided visitors with a tangible way to explore and understand symbolic and nonlinguistic mapping concepts that are central to the Lukasa by creating and sharing stories with each other through tangible and digital media.

Similar to the Lukasa, examples of physical artifacts that hold local stories and memories exist in other cultures as well, such as the visually striking portable storytelling "shrines" that are part of the "Kaavad Banchana," a more than 400 year old oral storytelling tradition from the Rajasthan state in India [Sabnani 2011, 2014]. Kaavad shrines (see Figure 4.5) – colorfully painted wooden boxes with many opening doors and panels that display visual narratives – are used by traveling storytellers to recount local folklore, family stories, and genealogies. As the storyteller weaves their tale, they open and close the panels, and point to the images of Gods, goddesses, saints, local heroes and others that are depicted on them. In this way, the shrines serve as a memory aid for the storytellers and listeners alike, keeping the family and community's stories alive across generations.

In the TEI context, there is a growing body of work on tangible narratives [Harley et al. 2016a], which explores how digital narratives can be experienced through digitally enhanced physical artifacts. For example, the Triangles system [Gorbet et al. 1998] allowed children to

Figure 4.4 The **Mapping Place** exhibition showcased an authentic African Lukasa (left) [Photo taken by Sidarth Kantamneni for the Robert C. Williams Museum of Papermaking] as well as a Lukasa-inspired tangible tabletop installation (right) [Chu et al. 2015b].

Figure 4.5 **Kaavad shrines**, shown closed (left) and open (right), are tangible storytelling boxes that are part of the oral storytelling tradition in Rajasthan [Sabnani 2011, 2014] [Photo Credit: Nina Sabnani].

Figure 4.6 **Triangles** (left) allowed children to explore non-linear stories by snapping together triangular tiles [Gorbet et al. 1998]. **Tangible Spatial Narratives** (middle) used physical pawns on an interactive tabletop to explore multi-threaded and spatially structured stories [Mazalek and Davenport 2003]. The **Cueb** interface supports photo sharing in everyday life [van den Hoven 2014] [Photo Credit: Connie Golsteijn].

explore stories in a non-linear way by snapping together triangular shaped tiles with illustrations depicting characters, settings, events and dialogue (see Figure 4.6, left). Other tangible narrative systems have used interaction with physical artifacts on interactive tabletop surfaces, such as Tangible Viewpoints [Mazalek et al. 2002] and Tangible Spatial Narratives [Mazalek and Davenport 2003], where the manipulation of physical pawns on a tabletop surface allowed users to experience multi-viewpoint and spatially structured stories (see Figure 4.6, middle). In all of these examples, the physical manipulation and re-configuration of physical artifacts served as a means for users to interactively navigate and make sense of a complex narrative space. Digitally-enhanced tangible artifacts have also been used to support human remembering by connecting to people's own memories and personal histories. For example, Cueb and 4Photos [van den Hoven 2014] both combine physical designs with computing to facilitate communication about the past through the use of material and digital memory cues (see Figure 4.6, right).

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Materialising Memories

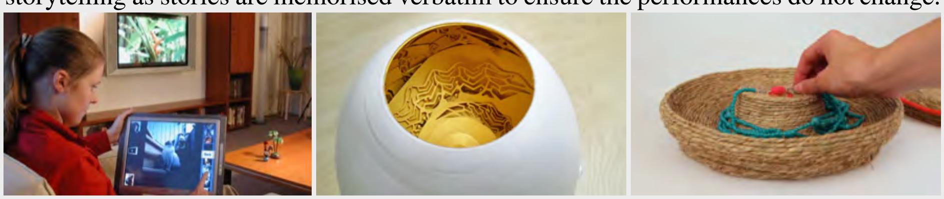
The Materialising Memories research program [van den Hoven 2014] integrates cognition research with TEI, to design for everyday remembering practices. This often engages autobiographical memory, the "memory for the events of one's life" [Conway and Rubin 1993]. It relates to individual identity, problem solving and future planning, and social functions such as dealing with relationships [Bluck 2003]. These functions are particularly relevant for TEI because of the prevalent use of digital media, digital services and interactive devices in remembering practices. However, because recognition requires less cognitive load compared to recall, remembering practices can be further enhanced by engaging with a physical presence. Materialising digital accumulations or providing physical reminders gives them a place in our everyday environment, making them easier to interact with or act upon.

The following examples integrate storytelling, personal remembering, embodied cognition and tangible interaction and support the social function of autobiographical memory. The tangible objects in these examples serve as memory cues [van den Hoven and Eggen 2014], to support remembering and the retrieval of information, and support different types of storytelling.

The Digital Photo Browser system [van den Hoven and Eggen 2003, 2008] (Figure 1, left) includes a tablet holding personal digital photo collections and a TV used to display individual photos. Electronically 'tagged' physical holiday souvenirs trigger the presentation of subsets of photos when placed on a coffee table. Both the souvenir objects and photos can cue specific memories and support remembering and storytelling. This system supports serendipitous conversational storytelling around photo archives and souvenirs, as happens when guests visit someone's home.

StoryShell [Moncur et al. 2015] (Figure 1, middle) is a bespoke design for a mourning mother to commemorate the death of her 15 year-old son, and to retain contact with his friends. It is a tangible device that plays audio recordings of friends' stories when the device senses it is being held. The StoryShell object is representative of the lost loved one and his relationship with his friends. It supports unsolicited, informal storytelling, by allowing the mother to listen to stories her son's friends share to remember him by.

StoryBeads [Reitsma et al. 2013] (Figure 1, right) is a recording device in the form of a basket. It is activated when an electronically tagged bead is placed on it. Stories are recorded onto the beads during traditional performances, to be listened to later, anywhere, anytime. The basket object supports and represents the oral-storytelling traditions of the South African BaNtwane culture, with each tagged bead representing a specific story that was traditionally shared around the campfire. It supports more formal and performative storytelling as stories are memorised verbatim to ensure the performances do not change.



From left to right: Digital Photo Browser [van den Hoven and Eggen 2008] [Photo Credit: Philips Research], StoryShell [Moncur et al. 2015], and StoryBeads [Reitsma et al. 2013] [Photo Credit: Lizette Reitsma].

These examples show the richness and breadth of how TEI can support storytelling and remembering practices. There is more to be done to support the social function of autobiographical memory [Bluck 2003], including having TEI research acknowledged and adopted by other disciplines.

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Figure 4.7 **Senet** (left). *Gaming Board Inscribed for Amenhotep III with Separate Sliding Drawer*, c. 1390-1353 B.C.E. Faience, 2 3/16 x 3 1/16 x 8 1/4 in. (5.5 x 7.7 x 21 cm). Brooklyn Museum, Charles Edwin Wilbour Fund, 49.56a-b. Creative Commons-BY (Photo: Brooklyn Museum, 49.56a-b_view2_SL4.jpg). **Depiction of the game of Senet** (right) in the tomb of Egyptian Queen Nefertari, c. 1298-1235 BC.

Social Play

Physical artifacts have also played an important role in framing and supporting leisure activities throughout history. We can look to board games as tangible mediators of game play and social activity. Archeological evidence such as tomb paintings and literary texts give us clues about the role that board games have played in society for over 3,000 years. For example, the game of Senet (see Figure 4.7) was popular among pharaohs in Ancient Egypt. Depictions typically show a pair of players sitting on opposite sides of the Senet board, with the gameplay sometimes shown in the context of funeral celebrations, alongside scenes of people engaged in other social activities such as singing, dancing, and playing music [Crist et al. 2016].

In board games, the physical board and playing pieces act as both material representations of the game state, as well as controls for moving the game forward. A typical gameplay convention, seen for example in the game of chess, is that a player's move remains open until they have released their piece. In this way, the physical pieces also serve as a cognitive aid, allowing players to better imagine potential outcomes by physically testing out their moves before committing to them.

In the TEI context, multi-touch and tangible tabletop platforms offer the opportunity to bring together the advantages of traditional board games, such as using physical pieces to represent and control game state and face-to-face social interaction, with the advantages of computer games, such as rich multimedia content and more complex computationally-driven game mechanics. For example, in the game Youtopia [Antle et al. 2013a], which we describe in Chapter 2, tangible and multi-touch interactions on a digital tabletop surface allow children to simulate and explore issues of sustainable land-use planning (see Figure 4.8). Through their

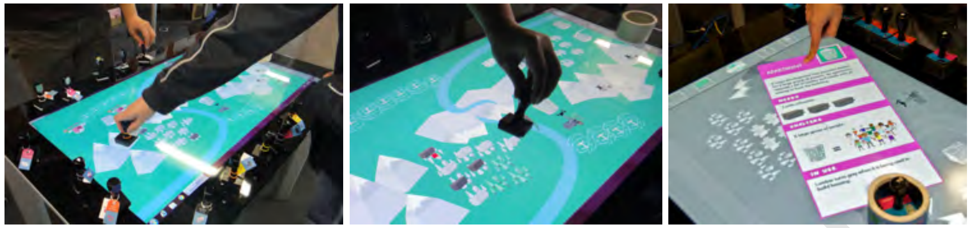


Figure 4.8 The **Youtopia** game uses a combination of tangible and multi-touch interaction on an interactive tabletop surface to allow children to simulate and explore issues of sustainable land-use planning [Antle et al. 2013a] [Photo Credit: Amanda Hall].

collaborative interactions, the children can reflect on and determine for themselves whether or not they are happy with the world they have created. The social-technical design strategies employed in the project thus allow children to work together through positive interdependence that includes value-based and critical reflection during collaboration.

Theoretical Foundations

In the previous section, we looked at examples of how we think, play and connect with each other through bodily engagement with, and material manipulation of, physical artifacts across different parts of our lived experience. We now turn to the theoretical foundations for the area of TEI. In particular, TEI reflects and draws on ideas that have been explored in philosophy, psychology and the cognitive sciences. These ideas are rooted in a rejection of the Cartesian separation between mind and body, also known as mind/body dualism, which is named after 17th century French philosopher Rene Descartes (1596-1650). In mind/body dualism, thinking is a process that happens in the brain, which maintains and works with an abstract representation of the world, and is separate from the inputs and outputs of the perceptual and motor systems.

Mind/body dualism has been critiqued within different fields and these critiques have followed different paths through history. One such path is rooted in the philosophical movement known as phenomenology and can be traced into the social sciences. We can follow a parallel path in psychology and the cognitive sciences that is rooted in early motor theories of cognition. The next sections are not intended as a comprehensive history of these trajectories, but rather aim to serve as a brief survey that will set the stage for a discussion of how these ideas have been picked up by HCI and TEI in section 4.4.

Phenomenology

Phenomenology is the branch of philosophy focused on the study of human experience that was founded by German philosopher Edmund Husserl (1859-1938) in the early 20th century. The mind/body dualism of Descartes was rooted in a representative theory of perception, which holds that we are not directly aware of objects in the world but rather of representations of objects in our minds. Husserl rejected this theory in favor of a view of consciousness as intentional and directed at things in the world. In his later work [Husserl 1936], he introduced the concept of "life-world" (lebenswelt), which represents the everyday world of human experience, both personal and intersubjective. Life-world is the dynamic and ever-changing social, cultural and historical background that we live in and from which our theoretical and scientific understanding of the world originates.

Phenomenological ideas were further developed by other philosophers in the 20th century, including Husserl's student Martin Heidegger (1889-1976), as well as Austrian philosopher Alfred Schutz (1899-1959) and French philosopher Maurice Merleau-Ponty (1908-1961). At the core of Heidegger's contribution to phenomenological thinking, elaborated in *Being and Time* [1927], was the concept of "being-in-the-world," or "Dasein," which emphasizes a way of knowing that is derived from our practical existence in the world, grounded in purposeful action. A characteristic of being-in-the-world is the state of "thrownness" (Geworfenheit), which captures the nature of human existence, where we are thrown into an already existing world and must act within it without a clear sense of what all the effects of our actions will be. Related to this, Heidegger distinguished between different ways of encountering things in the world and acting with them. Objects in the world are "ready-to-hand" (zuhanden) when we act through them, when they seem to disappear in the course of our actions with them. In contrast, objects in the world are "present-at-hand" (vorhanden) when we become conscious of them, when we attend to them and reflect on them.

In contrast to Husserl and Heidegger who both concentrated on individual experience, Alfred Schutz related phenomenological thinking to the social world and to the social sciences. He argued that our experience of the world includes our social interactions and understandings, and was thus concerned with how people can build shared meaning from their own experiences of the world [Schutz 1932]. Merleau-Ponty also built on Husserl and Heidegger's ideas, focusing on the role of the body in perception. For Merleau-Ponty, a sense of the body and bodily experience gives meaning to our perception of the world [Merleau-Ponty 1945b].

At the same time as these and other philosophers were formulating the core ideas of phenomenology, scientists and scholars in areas such as neuroscience, medicine and psychology were conducting early work on motor cognition. This is what we turn to next.

Motor Cognition

The work on motor cognition emerged in the mid-19th century and continued to develop into the early part of the 20th century [Scheerer 1984; Stock and Stock 2004]. Much of this early work was eclipsed by the behaviorist approaches to psychology that took hold in the first half of the 20th century. However, it has gained renewed interest in the cognitive science community over the past several decades.

The 19th century work in motor cognition can be traced along British and German paths that evolved in parallel and addressed related ideas. These paths are nicely reviewed by Stock and Stock [2004]. On the British side, physician and neurophysiologist Thomas Laycock (1812- 1876) observed that reflex-like actions in patients could be triggered by the imagination alone, and tried to come up with a physiological explanation for this [Laycock 1845]. He also speculated that there are bidirectional connections between sensations and movements. His colleague, physician and physiologist William Benjamin Carpenter (1813-1885), coined the term "ideo-motor", i.e. the triggering of actions by ideas. Carpenter differentiated ideo-motor reflexes from excito-motor and sensory-motor reflexes, and used the idea of ideo-motor reflexes to propose a scientific explanation for paranormal phenomena, like the movements of divining rods [Carpenter 1852]. On the German side, scientists looked at motor cognition more broadly to explain voluntary human behavior, and developed ideo-motor theory as a reaction against Cartesian mind/body dualism [Stock and Stock 2004]. Many of the central ideas were developed by philosopher and psychologist Johann Friedrich Herbart (1776- 1841), who described the mechanism as well as the developmental aspects of the control of action through ideas [Herbart 1825]. These ideas were further elaborated by others, such as philosopher Rudolf Hermann Lotze (1817-1881) and physiologist Emil Harless (1820-1862).

The ideas that were formulated in the British and German paths later converged in the thinking and writings of William James (1842-1910), an American philosopher and psychologist [James 1890]. Although James adopted the term ideo-motor from Carpenter, his focus was broader like that of the Germans, and he believed that all everyday actions can be considered ideo-motor actions. That is, he believed that mental images guide and trigger our movements (and thus our actions), as long as there is no conflicting mental image to prevent the movement. He summarized these ideas in what is called the ideo-motor principle of voluntary action: "every representation of a movement awakens in some degree the actual movement which is its object; and awakens it in a maximum degree whenever it is not kept from doing so by an antagonistic representation present simultaneously in the mind" [James 1890, p.526]. James also developed a theory of how our bodies affect our emotions. His core thesis on this idea was as follows: "*... the bodily changes follow directly the PERCEPTION of the exciting fact, and ... our feeling of the same changes as they occur IS the emotion*" [James 1884, pp.189-190, italics and emphasis in original].

Other work in the early 20th century focused on the somatosensory system and, notably, on the mental representations we hold of our own bodies and their position in space. These mental representations, termed "body schema," are used to plan and execute actions. This concept was first described by British neurologists Henry Head (1861-1940) and Gordon M. Holmes (1876-1965), and, of particular relevance to TEI, they noted that this representation is plastic and that it can be extended to include tools: "Anything which participates in the conscious movement of our bodies is added to the model of ourselves and becomes part of these schemata." [Head and Holmes 1911, p.188]

Despite this historical context and the fact that both philosophers and scientists throughout the 19th and early 20th century worked to overturn Cartesian mind/body dualism, it took a while for these ideas to find their way into the nascent area of HCI. In the next section, we look at the implications of phenomenology and the concept of the embodied mind on the area of HCI and more specifically TEI.

Implications for TEI

Early approaches to HCI were Cartesian in nature and rooted in cognitivism [Wallace et al. 2007], a theoretical position that views cognition as the manipulation of internal representations of things in the world, which serves to guide actions. From this perspective, the computational processing of information and the inputs and outputs to/from the computational system are modeled as separate entities, both conceptually and in practice. Examples include interaction models like GOMS (Goals, Operators, Methods and Selection rules) [car] and MVC (Model, View, Controller) [Burbeck 1987]. Similarly, classical Artificial Intelligence (AI) approaches built on the dualistic view of mind and body, maintaining that intelligent behavior could be implemented within a computational system alone, see e.g. Newell and Simon [1972].

Critiques of this view emerged in both the HCI and AI fields, grounded in the ideas of phenomenology and motor cognition described above. As such, we can continue to trace forward the philosophical and scientific paths examined above, looking at how they have been further developed, in particular with respect to the evolution and spread of computing technologies in society. Once again, we do not aim to provide a comprehensive overview of the research and scholarship in these areas. Rather, we aim to examine some of the key ideas that have been influential within HCI, and discuss their implications on the design of TEI techniques and applications. A nice overview of these trajectories can also be found in Marshall and Hornecker's *Theories of Embodiment in HCI* [2013].

From Phenomenology to TEI

As computing technologies have become increasingly pervasive and HCI has evolved to stay on top of the ever-changing technological landscape, a number of researchers have been instrumental in bringing the core ideas of phenomenology to HCI, and more recently TEI, research and design. This has helped to fuel a shift in the way we think about and describe our interactions with technology. We describe some key examples here.

Phenomenologically Grounded Design. Winograd and Flores played a key role in bringing phenomenological thinking to HCI, drawing on the writings of Heidegger. In *Understanding Computers and Cognition: a new foundation for design* [1986], they describe the way in which objects that are ready-to-hand will become present-at-hand in the event of a breakdown. They use the example of a word processor to illustrate these ideas in the context of technology. As long as the word processor is working normally, the writer will think only of the words appearing on screen. However, if a letter fails to appear on screen, then suddenly the complex network of equipment that makes the words appear on screen becomes present to the writer, and must be reflected on and attended to in order to deal with and fix the breakdown. Building on these ideas, they describe a foundation for design in which a clear objective is for designers to anticipate and plan for breakdowns by providing for possible actions that users might take when the computer system fails to work as expected.

Social and Situated Practice. Sociologist Harold Garfinkel picked up on Alfred Schutz's work connecting phenomenology to our understanding of the social world, and formulated ethnomethodology as an approach for sociological study that is grounded in the everyday practices people engage in together in order to achieve social order [Garfinkel 1967]. HCI researchers have drawn on this approach in studying our interactions with computational systems. In particular, Suchman drew on ethnomethodology and conversation analysis [Sacks 1992] in analyzing user interactions with a photocopier, revealing a mismatch between the fixed model implemented in the system and the user's fluid behavior in confronting it [Suchman 1987]. Her work offers a strong critique of cognitivism, highlighting the fact that while plans (i.e., internal representations) can serve to guide action, they do not strictly determine action. Instead, behavior is an improvised activity that arises within a given context, and actions are thus situated.

In the TEI context, Hornecker and Buur [2006b] interweave the social and expressive nature with the physical and material nature of tangibles, viewing tangible systems as resources for shared sense-making. Similarly, Van Dijk et al. [2014] describe design from the perspective of "socially situated practice." This view reverses the way HCI designers have traditionally thought about designing computer systems, with their emphasis being on how to provide ways for users to access digital information. Instead, they propose that design should consider how computer systems can connect to people's existing embodied and social practices in the world (see Figure 4.9, left). They use the Reactable as an example of design that supports socially situated practice, describing the way in which meaning is co-constructed within a performance setting by groups of musicians [Xambó et al. 2013] (see Figure 4.9, right).

Embodied Metaphor and Interaction Design. Metaphors have played an important role in interface design since the early days of graphical user interfaces. For example, the desktop and file system metaphors help users understand their computer interactions in terms of concepts and objects that are familiar from their real world experience. The work of Lakoff and Johnson [1980; 1999] has investigated the role that metaphors play in cognition, suggesting that abstract thought is grounded in our bodily experience. In particular, they suggest that abstract concepts are related to basic image schemas (also called embodied schemas) by metaphorical mappings. These image schemas are sensorimotor patterns that organize our experience and understanding of the world, giving rise to a conceptual representation. They involve our body's movement in space, our perceptual experiences, and our manipulation of objects. They can be classified into different groups according to their experiential basis, such as containment, space, force, attribute, etc. [Hurtienne 2017; Hurtienne and Israel 2007] (see Figure 4.10). Embodied metaphors map these embodied experiences onto a more abstract target domain.

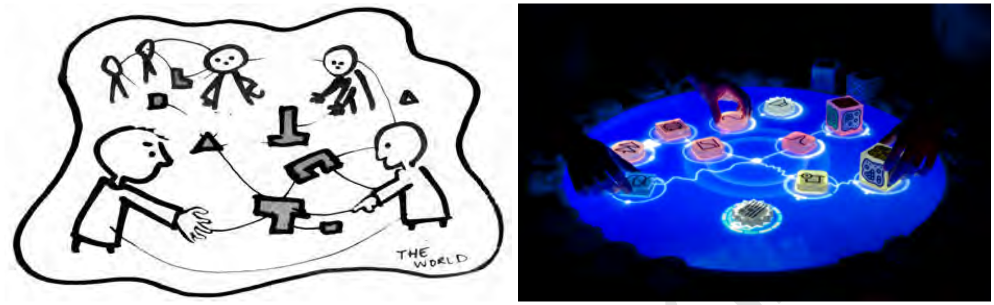


Figure 4.9 An illustration of **Socially Situated Practice** (left) from Van Dijk et al. [2014]. Design from the perspective of socially situated practice should consider how computer systems can connect to people's embodied practices in the world [Image Credit: Jelle Van Dijk]. The **Reactable** (right) serves as an example of design that supports socially situated practice as it enables collaborative construction of meaning during live performances [Van Dijk et al. 2014] [Photo Credit: Xavier Sivecas].

For example, proximity maps onto similarity, warmth maps onto affection, and up maps onto good (versus down for bad).

From the TEI perspective, Hurtienne and Israel proposed using image schemas and their metaphorical mappings as a framework for both analyzing and designing tangible interfaces [Hurtienne and Israel 2007]. They suggest that space and containment schemas are particularly interesting for tangible interface design since our interactions with tangibles necessarily take place in space and involve collections of related objects. Moreover, containers are often used in tangible interactions and are seen in other tangible interaction frameworks (see e.g. [Holmquist et al. 1999; Shaer et al. 2004b; Ullmer et al. 2005b]). Work by Bakker et al. [2012] has furthered the idea of using embodied metaphors in tangible interaction design. Specifically, they propose an iterative and user-centered approach for designing interaction models that are based in embodied metaphors. They describe a process that begins with enactment studies to identify relevant metaphors and follows through with the design and evaluation of prototypes of increasing fidelity.

Embodiment in Tangible and Social Computing. In his book *Where the Action Is: The Foundations of Embodied Interaction* [2001a], Paul Dourish provides a detailed discussion of Husserl, Heidegger, Schutz and Merleau-Ponty's ideas. He reflects on the different ways that the concept of embodiment plays a role in their thinking, while at the same time noting their shared emphasis on the relationship between embodied action and meaning. As Dourish discusses, a central idea for these phenomenologists is that meaning exists in the world and arises through our embodied actions with the world and with each other. Based on this, he argues that phenomenology provides a starting point for understanding embodied

Group	Image Schemas
BASIC SCHEMAS	SUBSTANCE, OBJECT
SPACE	UP-DOWN, LEFT-RIGHT, NEAR-FAR, FRONT-BACK, CENTER-PERIPHERY, STRAIGHT-CURVED, CONTACT, PATH, SCALE, LOCATION
CONTAINMENT	CONTAINER, IN-OUT, CONTENT, FULL-EMPTY, SURFACE
IDENTITY	FACE, MATCHING
MULTIPLICITY	MERGING, COLLECTION, SPLITTING, PART-WHOLE, COUNT-MASS, LINKAGE
PROCESS	SUPERIMPOSITION, ITERATION, CYCLE
FORCE	DIVERSION, COUNTERFORCE, RESTRAINT REMOVAL, RESISTANCE, ATTRACTION, COMPULSION, BLOCKAGE, BALANCE, MOMENTUM, ENABLEMENT
ATTRIBUTE	HEAVY-LIGHT, DARK-BRIGHT, BIG-SMALL, WARM-COLD, STRONG-WEAK

Figure 4.10 List of **image schemas** grouped by similarity from [Hurtienne and Israel 2007]. Image schemas are abstract representations of recurring sensorimotor patterns that help organize our experience and understanding of the world.

interaction, and that tangible and social computing in particular share a common ground in phenomenological thinking.

Extending these concepts, Klemmer et al. [2006] have discussed the benefits of the physical world that are relevant for interaction design, synthesizing them into themes that address both the individual and social aspects of bodily actions. Importantly, they note that designers should be careful about unreflectively replacing the physical world, and should instead consider how their solutions can integrate the physical and digital worlds, all the while leaving the physical world untouched to the extent possible. Similarly, Fernaeus et al. [2008] describe an action-centric perspective on tangible interaction design, which is in direct contrast to a data-centric approach that views interaction design from an information processing perspective. They describe tangibles as resources for action, emphasizing that designers need to consider how users make meaning through their interactions with the system.

From Embodied Cognition to TEI

We have looked at how the philosophical ideas of phenomenology have made their way into TEI. In this section, we turn to the cognitive aspects that underlie the phenomenological position. The concept of a link between action and imagination that was described by James and his predecessors, as well as the work on body schemas by Head and Holmes, can be traced forward to a range of both theoretical and empirical work in the cognitive sciences. This work is broadly captured by the term "embodied cognition," and by other similar terms such as "enaction" and "embodied mind" [Varela et al. 1991] as well as "extended mind" [Clark and Chalmers 1998]. Given the sheer breadth of related work, there is so far no unified view of embodied cognition. Nevertheless, Shapiro [2011] provides a nice overview of the different concepts and debates. Here we are not concerned with these debates, but rather provide a brief overview of several threads of recent work in embodied cognition and discuss their relevance and implications for TEI.

Ecological Psychology and Affordances. Although it may no longer be considered contemporary, an important milestone that has been influential in the context of embodied cognition is the work of American psychologist James J. Gibson (1904-1979) on the relationship between perception and action. Gibson advanced the idea that perception is contingent on being and acting, as well as on the given and immediate environment as a whole. These ideas served as a foundation for an "ecological" approach to psychology [Gibson 1979a]. Perhaps most importantly in the context of HCI, Gibson coined the term "affordance," which he described as follows: "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment." [Gibson 1979a, p.127]

Don Norman [1988b; 1993] later adopted the concept of affordance (or more specifically, perceived affordance) when considering how the form of an artifact suggests its function and use. Although this is how the term "affordance" was introduced to the HCI community, this view is limited as it suggests that affordances are like "messages" encoded in the physical form of artifacts [Van Dijk et al. 2014]. As we will see later in this section, affordances are dependent on and need to be considered in the much more nuanced context of a person's moment-to-moment circumstances and the way they are acting in the world over time. Indeed, Norman later revised his terminology to reflect the dynamic nature of the physical and social world in which we interact by proposing that the term "signifiers" can serve as a more suitable design principle than "affordances" [Norman 2008]. According to Norman, a "signifier" is any kind of physical or social indicator, be it intentionally placed by the designer or merely accidental, that can help people understand how things in the world work and that can guide people's behavior.

External Representations and Distributed Cognition. In his book *Microcognition: Philosophy, Cognitive Science and Parallel Distributed Processing* [1989], Andy Clark uses the example of a human solving a jigsaw puzzle to illustrate the importance of environmental structures in our cognitive processes. Creating a model of puzzle solving that disallows manipulation of real physical pieces would require constructing a complete internal representation of the shape and visual properties of every single puzzle piece. While the puzzle could be solved in this way, the solving process would be nothing like the process a person would follow to solve the puzzle. To solve a jigsaw puzzle, we combine our internal thought processes with physical actions on objects in the world. Through these physical actions, we test hypotheses and generate new states of information that in turn feed our internal processes. This is the central idea underlying the theory of distributed cognition proposed by Edwin Hutchins in *Cognition in the Wild* [1995]. Hutchins' formulation of distributed cognition was informed by his studies of the way intelligent behavior arises among a team of navigators on board a naval ship. The theory of distributed cognition views thinking as information processing that combines both internal and external representations. That is, cognition is distributed between the brain and the environment, including the brains and bodies of multiple people, as well as physical objects and technologies. Hollan et al. [2000] subsequently proposed distributed cognition as a theoretical foundation for HCI research, using a combination of ethnographic studies and controlled experiments to support the design of collaborative digital systems. They emphasized the importance of "in the wild" observations of people's activities in a given design context, in order to gain an understanding of how cognitive processes evolve over time and are distributed across internal and external structures as well as social groups.

In related work, Kirsh and Maglio [1994b] looked at how interactions with external representations can support cognition. They showed that in the game of Tetris, players use what they called *epistemic actions* to re-organize the environment and reduce mental computation (see Figure 4.11, left). These actions include some of the rotations and translations of blocks that players make which do not directly bring them closer to their goal of fitting a block into a particular spot. In contrast, *pragmatic actions* have as main purpose to bring the player closer to their goal. Of particular relevance to TEI, Antle and Wang [2013] compared motor-cognitive strategies in a tangible vs. a multi-touch puzzle-solving task by classifying the actions users made with their hands (see Figure 4.11, right). They found that the tangible interface resulted in more effective and efficient interleaving of pragmatic and epistemic actions, and suggest that the efficiencies result from the use of physical structures (like table edges) for organization as well as the 3D and tactile features of the tangible interface. Esteves et al. [2015] subsequently built on this work to develop the Artifact, Body, Tool (ATB) framework, a video-coding framework for identifying and measuring different epistemic actions during problem-solving tasks.

The Enactive Approach and Design for Sensorimotor Coupling. Related to Gibson's insight that perception is active and grounded in the possibilities for action provided by the environment, the enactive approach proposed by Varela et al. [1991] considers cognition as an ongoing process of being coupled to the environment through sensorimotor activity. This idea underlies behavior-based robotics, in which robots navigate the world without internally representing and planning actions, but rather through direct sensorimotor interaction with the environment [Brooks 1991]. The way in which sensorimotor interaction with the environment

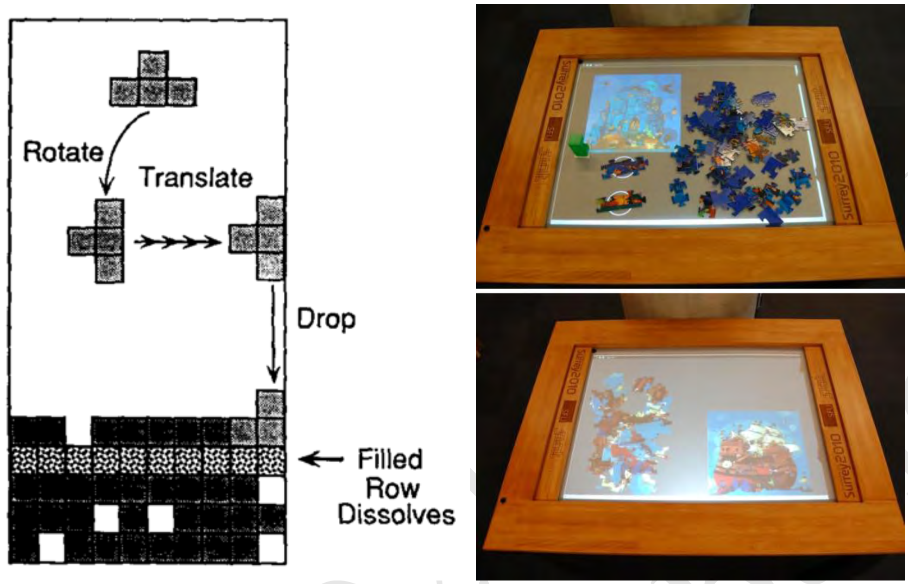


Figure 4.11 Kirsh and Maglio [1994b] looked at how interactions with the game of Tetris support cognition (left), distinguishing between *epistemic actions* that re-organize the environment and reduce cognitive load, and *pragmatic actions* that bring the player closer to their goal. Antle and Wang [2013] compared a tangible vs. multi-touch puzzle solving task (right), finding that specific features of the tangible interface enabled more effective pragmatic and epistemic motor-cognitive strategies [Photo Credit: Sijie Wang].

can replace representation can be illustrated by considering how baseball outfielders catch a fly ball: instead of relying on a purely computational approach, they simply run in a way that keeps the ball in a straight horizontal line in their visual field [Clark 1997; McBeath et al. 1995]. In this way, they can make continual adjustments to their running trajectory and speed based on their visual perception, and thus end up exactly where they need to be in order to catch the ball before it lands.

In the TEI context, Van Dijk et al. [2014] describe design based on “sensorimotor coupling and enactment” as design in which meaning is not pre-defined, but rather arises in the interactions between users and products (see Figure 4.12). They note that this perspective can allow a more nuanced understanding of the term “affordance” discussed above. The way a person sees the world and the objects within it depends on how they are acting within it at any given moment. As result, the world and objects within it will show up as affording certain actions based not only on what is encoded into their physical form in a fixed way, but also based on the current sensorimotor coupling in place. So for example, a steep hill might seem climbable or not based on whether or not one puts a heavy pack on their back.

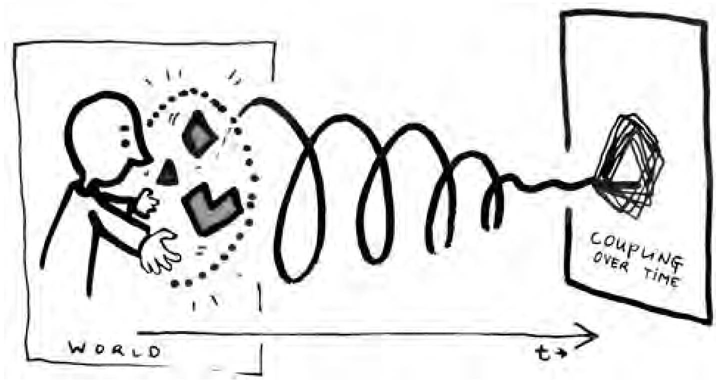


Figure 4.12 An illustration of **Sensorimotor Coupling and Enactment** from Van Dijk et al. [2014]. Design from this perspective takes into account that meaning arises in the interaction between users and products [Image Credit: Jelle Van Dijk].

Like in the case of the baseball outfielder's ongoing coupling to the ball in play, a designed system should tap into the sensorimotor couplings that emerge in ongoing interaction between the users and the system. Watson and Crick's use of balls and sticks to construct a model of the structure of DNA is a nice example of sensorimotor coupling in a discovery context, because their conceptual understanding of the structure was both externalized in the model, at the same time as their manipulations of the model further fueled their conceptual understanding. The Active Pathways system [Mehta et al. 2016a] extends this idea to designing for problems that are dynamic in nature, where computation plays an important part of the discovery process. In Pathways, the users' ongoing physical manipulations of the system (e.g., using tangibles on a tabletop surface to create reactions between molecules, or to adjust parameters in the dynamic system) allow them to work in partnership with the system in order to further their conceptual understanding of the biological system they are modeling, while at the same time increasing the accuracy of their computational model.

Tool Use and the Enactive Landscape. An important aspect of the enactive approach is that it recognizes that our goals, interest and attention shape our perception. The phenomena of change blindness and inattentional blindness are effects of this. We often miss changes that happen in front of our eyes when there is a visual distraction, such as changes introduced into arrays of letters while the display is flickering on and off [Pashler 1988]. This is called change blindness. We can also miss visually obvious things happening in our environment when our attention is focused on something specific, such as missing the fact that there is a person dressed like a gorilla nearby because our attention is focused on the passing of a basketball [Simons and Chabris 1999]. This is called inattentional blindness. When taken together, the result of change blindness and inattentional blindness is that we only perceive a part of what is available to be perceived in the world.

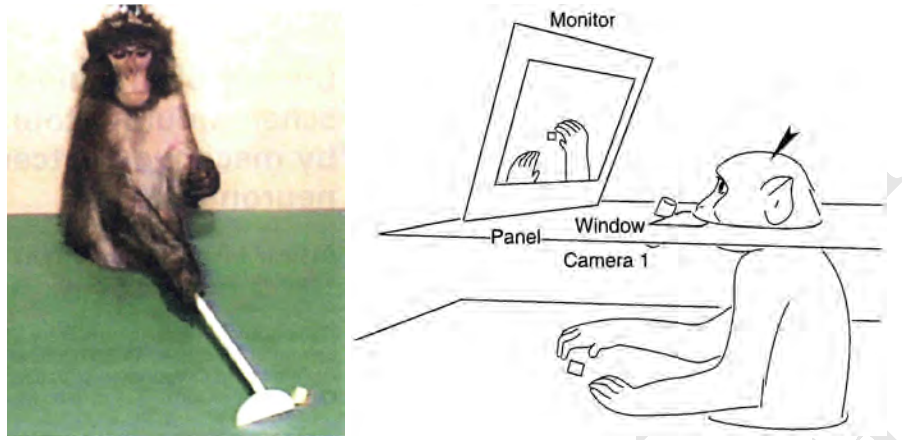


Figure 4.13 Iriki et al. [1996] showed that monkeys expand the representation of the space around their body to include the space around the tip of a rake after having actively used the rake to reach for an object (left). Iriki et al. [2001] also showed that a monkey's brain can treat a large virtual hand as its own (right).

Based on this, Kirsh [2013] introduced the idea of the "enactive landscape" as a way to capture the goal, activity and skill dependent nature of our perceptual experience of the world. As he suggests, this idea is important for designers to consider, because the tools we use and our level of expertise reshape our enactive landscape, changing our perception as well as our conception of what is possible. This draws on the idea of body schema described by Head and Holmes [1911] and the related concept of peripersonal space, which describes the region of space immediately surrounding the body and is viewed as a kind of interface for bodily interactions with objects that are within reach [Cardinali et al. 2009]. In seminal work with macaque monkeys, Iriki et al. [1996] found that the neurons coding the space near the hands of the monkeys expanded their representation to include objects near the tip of a rake, but only when the monkeys actively used the rake to perform an action (see Figure 4.13, left). This highlights the importance of purposeful interaction with the tool in order to essentially "absorb" the tool into the body's peripersonal space and incorporate it into the body schema. Further research has looked at how body changes and extensions can affect our sense of our own bodies and the world. For example, Iriki et al. [2001] showed that a monkey's brain can treat a large virtual hand as its own (see Figure 4.13, right), and van der Hoort et al. [2011] showed that changing our own body size affects how we perceive the world.

These ideas have some interesting implications for TEI research. For one thing, investigating if and when the tools and interfaces we are designing are incorporated into our peripersonal space might help us understand how natural and intuitive they are. Investigating tool absorption can also help us better understand the relationship between virtual and physical tools, as well as the role of practice and skill. Preliminary work related to these ideas has been con-

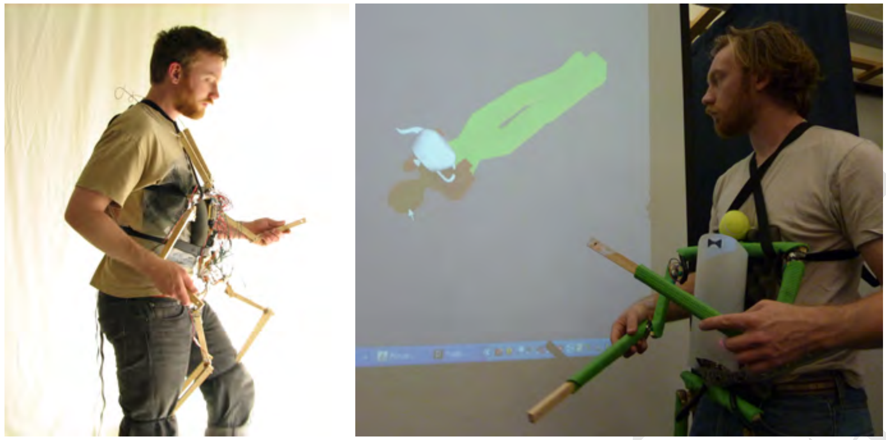


Figure 4.14 A **tangible puppet interface** (left) maps players own movements onto a virtual avatar. Using the puppet to play a game that causes the player to experience novel rotation patterns (right) has been shown to improve performance on a mental rotation test [Mazalek et al. 2011].

ducted in the TEI context. Mazalek et al. [2013] showed that practice with a virtual rake is sufficient to induce absorption of a similar physical tool into one's peripersonal space. Ayman et al. [2017] provide a definition of tool embodiment based on a measure of attention to the task vs. attention to the tool. They studied this in both physical and virtual tool conditions using a wrench-like tool, finding that in both cases participants shifted their attention to the task, which they took to be an indication of tool embodiment.

Common Coding as a Framework for Design. The 19th century work on motor cognition and the action/imagination link can be traced to the common coding theory formulated by Wolfgang Prinz and his colleagues at the Max Planck Institute for Human Cognitive and Brain Sciences. Stated simply, common coding theory posits a shared representation in the brain that connects an organism's movements (action), its observation of movements (perception), and its imagination of movements [Prinz 1992, 2005]. As described by Chandrasekharan et al. [2010], the central outcome of common coding is a kind of "body-based resonance," in which the body instantly replicates all movements it detects (without necessarily overtly executing these movements). This replication generates an internal representation that is dynamic and based on body coordinates, and which can later be used in cognition. Common coding can explain people's ability to recognize their own movements even in an abstract form, such as a walking figure shown as points of light at key points of articulation. Mazalek et al. [2009] showed that people can identify not only their own body movements when presented in this abstracted form, but also the movements of a puppet they controlled. Common coding has also been shown to stretch across individuals in a shared task, even though people coordinate better with their own movements [2006].

What is perhaps most interesting about this theory in the context of TEI is that it describes a neural mechanism that underlies embodied cognition, and this neural mechanism can serve as a kind of framework for designers. Indeed, Chandrasekharan et al. [2010] discuss the relevance and applicability of common coding to HCI and videogame design, suggesting that the common coding mechanism can account for three cognitive effects of videogames: a preference effect (the connection players form with their virtual avatars), a cognitive augmentation effect (the way players extend their abilities through the game), and a discovery effect (the way players discover new ways of doing things through the game). In particular, they suggest that designers can leverage the common coding mechanism to design novel interactions and video games that enhance players' cognitive abilities. Building on these ideas, Mazalek et al. [2011] and Chang et al. [2017b] have shown how virtual characters that encode players' own movements can improve spatial abilities when those virtual characters are placed in spatial situations that would be impossible for the player to experience in the real world. For example, when players experience novel rotation patterns through a virtual avatar that maps their own movements via a puppet interface, they improve their performance on a mental rotation test (see Figure 4.14) [Mazalek et al. 2011]. Although the results are quite preliminary, these studies show promise in using the common coding mechanism to tap into and augment a person's spatial abilities through a combination of tangible interfaces and virtual environments. Related to these ideas, Kirsh [2012] has shown through studies with dancers that visual perception of movements alone is not enough and that the involvement of the motor system is critical to learning. He suggests this may be because kinesthetic factors such as rapidly changing forces in our environment or bodies are difficult to detect visually and thus need to be picked up kinesthetically through actual movement.

Moving Forward

Beyond current theories, it is important to note that recent and future scientific and technological developments will, in turn, further influence our insights and theories. As Don Idhe explains, the interpretation of science and technology changed over the last century, and likewise, we should also investigate philosophy from a contemporary perspective. Philosophy changes with its historical context, and subsequently, Idhe proposes postphenomenology, integrating phenomenology and pragmatism and posing a new contemporary philosophy [Ihde 2009]. Robert Rosenberger, Peter-Paul Verbeek, Don Ihde et al. [2015b] further elaborate on this new perspective in their book *Postphenomenological Investigations*, in which they explore new human-technology including embodiment relations, hermeneutic relations, alterity relations, and background relations [Ihde 1990]. Rosenberger and Verbeek introduce cyborg relations, which can either refer to a 'fusion' relation, where the technology becomes one with the person and a new hybrid identity, the cyborg, emerges; or it can refer to an 'immersion' relation, where the technology merges with the environment, resulting in an interactive smart environment, where people can act upon. The TEI community should refine and develop new theories to address such new human-technology relations.

One last seed we want to plant coming from theoretical development is the name of this chapter *"Theories of embodiment"*. Is embodiment the appropriate label to use for our work? And does it give any handles for designing? Kristina Höök made a plea during her keynote talk at TEI 2020 to go beyond the terms embodiment and embodied interaction. It is not that she questions our bodied being in the world. As Merleau-Ponty [Merleau-Ponty 1945b] was stating, we have our own points of view from which we perceive and conceive the world, and we do perceive ourselves and others as mere objects in the world [Matthews 2006]. Her point is that embodiment and embodied interaction are closed terms that do not give direction to the quality of interaction [Höök 2018b]. *Embodied interaction as proposed by Dourish combines tangible interaction (addressing the "whole body") and social computing (addressing the "in the world"). Offered as an analytical concept, but without any "direction" or ideal associated with it. It does not answer questions like: Is a tangible interaction *better* than one that is entirely symbolic? If you speak to Dourish about it, his position is that any interface can become "embodied" with the user, even if some demand more work. The dashboard of a car becomes part of us even if it is entirely symbolic. We learn the connections by and by.* [Höök, personal communication]. Hence, Kristina Höök moved to somaesthetics by Shusterman [2008], as a more generative concept that could serve as a direction for what the "gold standard" of an interaction could be, even though it might not work for all design domains, e.g. it is unclear how appropriate it is for language-/symbolic-oriented designs). *Aesthetics in the way Shusterman speaks of it, concerns how we can live a better life. That we can improve on our somas. That we can experience *more* if we attend to our senses, if we develop them, if we move. This helped me see that: 1) as a designer, I can become better if I attend to my own somaesthetic appreciation of myself, of others, and of the materials we use to build systems; and 2) what I design should give end-users the same opportunity: to improve on their somas.* [Höök, personal communication]. Somaesthetics will be further explained in chapter 6.

Höök's plea for going beyond embodiment is supported by other researchers, including anthropologists Sheets-Johnstone and Ingold. Ingold [2013] is inspired by Sheets-Johnstone stating that *"animacy and embodiment pull in opposite directions: where the former is a movement of opening, the latter is bent on closure. For the living, animate beings we are, argues dance philosopher Maxine Sheets-Johnstone, the term 'embodiment' is simply not experientially apposite. We do not, she insists, experience ourselves and one another as 'packaged' but as moving and moved, in ongoing response - that is in correspondence - with the things around us"* [Ingold 2013; Sheets-Johnstone 1998]. We don't expect a quick renaming of the TEI field, but we do invite the researchers and practitioners in the community to discuss its foundations and the consequences of specific wording, in order to keep on developing including questioning its own implicit assumptions.

Summary

This chapter opened with a series of examples that illustrate some of the ways in which we think, play and connect with each other through bodily engagement with and manipulation of physical artifacts, particularly across the areas of discovery and learning, design and making, storytelling and memory, and social play. We then delved into the theoretical underpinnings of TEI, highlighting key ideas from philosophy and cognition, including phenomenology and embodiment, that have been influential on the development of TEI concepts, techniques and applications. We concluded with a brief discussion of forward-looking perspectives, such as postphenomenology, that can help TEI continually reflect on and potentially re-envision its underlying conceptual foundations.

5 Mediating Technologies

Most TEI systems are fundamentally entangled with physical artifacts. Where we have discussed many grounding examples and theories, the question of how tangibles are designed, fabricated, and brought to life is deeply central. Each of these topics is independently worthy of dedicated book(s). Here, we seek to provide a high-level overview, focused largely on mediating technologies, with some high-level consideration of design and fabrication.

We anticipate readers with widely diverse backgrounds. We imagine perhaps a third of readers already have deep expertise and experience in product design, physical fabrication, software, and/or electronics; perhaps a third have no background in some or most of these areas; and the most generous third have backgrounds somewhere in between. Accordingly, we have attempted to engage each of these subaudiences, at varying levels.

Introduction

TEI is brought to life by a wide, rapidly evolving array of technologies. These include several major technological realms:

- *sensing:* how is the presence, identity, and configuration of tangibles detected?
- *display:* how are the visual appearance and (sometimes) acoustical+olfactory environments of tangibles mediated?
- *actuation:* how are the physical states of tangibles (e.g., position, vibration) computationally effected?
- *computation:* how and where is the computation underlying the system realized?
- *communications:* how do system components communicate and interoperate both with each other, and with the larger networks (and/or the Internet)?
- *physical fabrication:* how are the tangibles of the system fabricated?
- *technology toolkits:* what styles of technology toolkits (hardware, firmware, or software) hold relevance to the creation of TEI systems?

Not all TEI systems incorporate technological interventions in all of these areas. Also, from conceptual, cognitive, technical, and aesthetic perspectives, well-designed tangibles frequently engage a delicate balance between exposing and rendering transparent their specific enabling technologies.

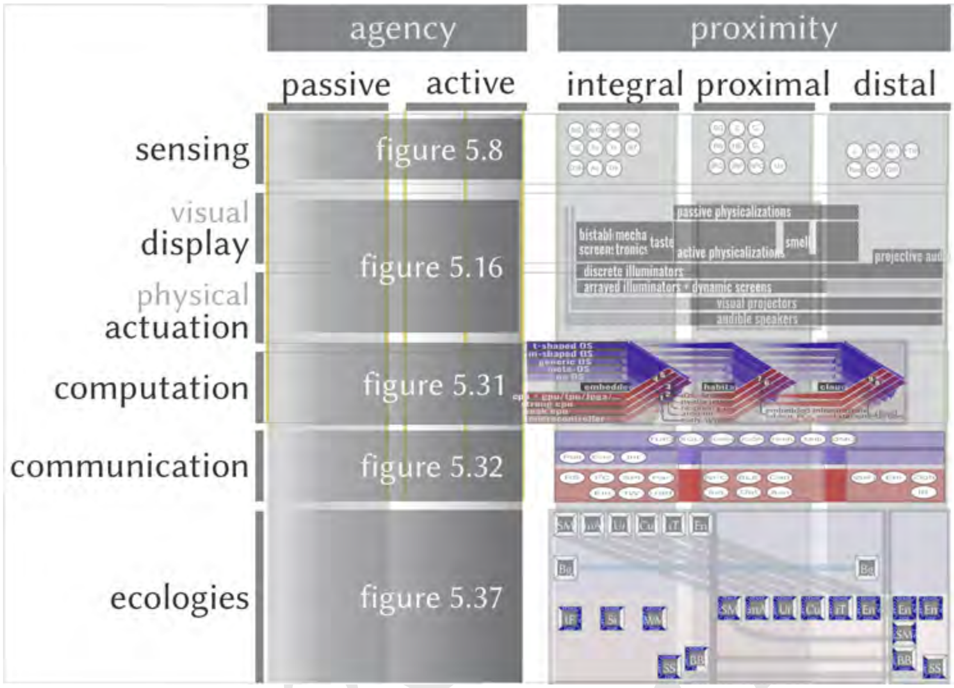


Figure 5.1 **TEI technology+mediation design spectrum:** *vertical axis identifies six technology, mediation, and fabrication facets underlying TEI systems. Horizontal axis identifies two cross-cutting factors: passive vs. active technologies ("agency"); and the proximity of these technologies to tangibles and/or people. "Active" can be regarded as matter of degree; it is loosely annotated as three relative levels. "Passive" and "active" are less directly applied to fabrication; here, we use the parallel terms "manual" and "CNC" (computer-numerically controlled; an aged term, but one indicating the role of computational technology).*

These technology and mediation facets are illustrated in Figure 5.1. We next discuss these, both relative to Figure 5.1 and technology particulars specific to each facet, before returning to consider how these complementary facets come together within the design of TEI systems.

On "mediating" and "mediation"

We have chosen *mediating* as the first word of this chapter. Our use of this term, and many of the technology discussions of this chapter, may benefit from a grounding example. Imagine one has a close relative who lives overseas (whether a mother, sister, grandaughter, etc.). At present, there is often no incremental monetary cost for sustaining such an audio or video session. In parallel, many of us have a scarcity of time and attention amidst all the traditional demands of the physical world, compounded with endless channels of streaming digital media[1]. And some of us (especially the very young and old) at times have less human contact than might be desired. At present, is this overseas relative (say, a sister):

- awake?
- reading something?
- writing something?
- cooking something?
- moving somewhere?
- speaking with someone?

Each of these potentially have practical import. In the context of a close relative, where a next physical visit might be months, years, or decades away, one might wish:

- to avoid calling the sister when she is asleep;
- to be aware if she is engaged in various activities (unless these are private);
- to seek new ways to keep in contact, as enabled by various technologies, recollecting that often the "medium is the message."

Clearly, the sister is a *person*. She is not "digital information;" but there is much digital information surrounding both the sister herself, and the virtual and physical artifacts with which she interacts, that can be *mediated*. A formal – if abstract – definition of "mediate" aligned with our use is "to effect (a result) or convey (a message, gift, etc.) by or as if by an intermediary" [dictionary.com]. To make this more concrete, we consider several illustrative examples of mediating remote human presence through diverse tangible "intermediaries."

The Switch that Lights

One could argue that a light switch and overhead light are among the simplest of sensors and displays. In common architectural use, it is not uncommon for a single room to have multiple lights, mutually controlled by switches at each of several entrances. It is also increasingly common that the switches be connected to the Internet – e.g., as "smart WiFi light switches" – allowing them to be remotely controlled for convenience and security.

Imagine that these switches and lights are redistributed between two rooms – one in our home, and one in that of our overseas sister. In this "shared room," switching either light switch (here or there) turns overhead lights on or off in both rooms. Even with this simple perturbation, we weave a kind of ghostly presence between the two spaces, allowing us to indirectly observe and participate in comings and goings an ocean away.

[1] here, the sense of "channel" we engage is along the lines of "a means of communication or expression: such as (1): a path along which information (such as data or music) in the form of an electrical signal passes" [merriam webster.com]. This includes common uses such as television, radio, and streaming music channels; but also includes teleconferencing, diverse digital files, etc.

Tangible telepresence

Our switch-and-light examples offer highly abstract mediations of remote presence. Conversely, Figure 5.2 illustrates three different more literal approaches to tangible telepresence.

The "talking heads" example, first implemented ca. 1979 at the Architecture Machine (ArchMac) Project predecessor to the MIT Media Lab [of Digital Art ADA], was a gimbal-actuated, back-projected array of translucent face masks (Figure 5.2a). The system enabled five people in distributed locations to sit about a conference table, with actuation supporting (e.g.) the nodding and shaking of heads, and projective illumination communicating gaze and lip movement.

Danny Rozin's "Trash Mirror No. 3," is a mechatronic mirror made of 500 actuated discarded objects (Figure 5.2c). Often sensed by cameras or Microsoft Kinects, Rozin's systems mechatronically actuate artifacts ranging from wooden tiles to pom poms as interactive reflections of human presence. While Talking Heads and Trash Mirror offer proximal interactivity, inFORM enables manual interaction with local and remote bodies and physical artifacts (Figure 5.2b) [Ishii et al. 2015a].

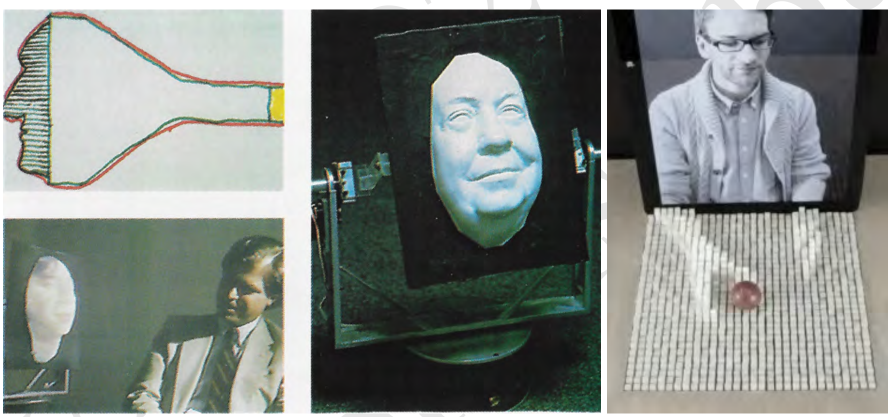


Figure 5.2 **tangible telepresence:** a) "talking heads" teleconferencing system [Brand 1987; Naimark 2005]; b) inFORM [Leithinger et al.]

In practice (with principle): an example system

In the next sections, we survey enabling technologies that contribute to the creation, sensing, and active computational mediation of tangibles. Encyclopedias spanning thousands of pages have been written on sensor, display, computer, fabrication, and other relevant enabling technologies. We are unclear whether any list, however minimal or verbose, can alone facilitate implementation of real TEI systems in classroom, hobbyist, scientific, industrial, or other applied contexts. Toward illustrating how underlying technologies can be applied, we next briefly introduce an example TEI system, Enodia, created toward four primary ends:

1. *classroom utility:* Enodia's elements have been evolved to facilitate teaching TEI in diverse classrooms, alternately focusing on interactive systems, software design, electronics, fabrication, graphic design, product design, and operating systems, among others.
2. *applied scientific utility*: Enodia has initially been developed at a number of institutions to facilitate research with diverse scientific subjects (e.g., genomics and astrophysics).
3. *economic, reproducible implementation:* Early TEI systems often required expensive hardware (sometimes $\gg$ US$100,000), with fabrication unlikely to be reproducible. With Enodia, a system with multiple tangibles (including computers, sensors, and displays) has roughly the cost of an average hardback book, and rapid fabrication via many alternate tools. The largest example (~$20 \times 16 \times 8$ ft, or ~$6 \times 5 \times 2$m), including dozens of motors and displays, has roughly the material cost of a high-end laptop computer.
4. *generalizability and scalability:* The last few decades have born witness to the remarkable growth of the Internet, web, and social media. Many decisions – e.g., the use of 8 bit, 32 bit, or 128 bit Internet addresses for computers – have held profound implications for generalizability and scalability. We see similar questions, on multiple fronts (e.g., scalability on technical, functional, and environmental fronts), of high TEI relevance.

Several illustrations of Enodia variants appear below; many others, with additional context, appear in the Appendix. In the next subsections, we briefly consider its use of cyberphysical tokens, constraints, and ecologies.

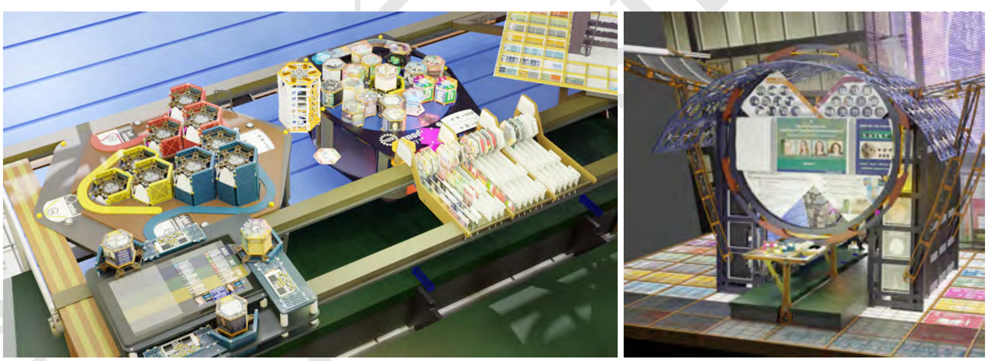


Figure 5.3 **Enodia examples:** a) Several interfaces for engaging with Enodia's hextok tangibles within a railed table. b) External view of Ferntor Shelter, with table extended to outside and Oculus pivoted to front for outside teaching. Further elaboration is provided in the Appendix.

Sensing

Sensing is the process by which a TEI system acquires data regarding the state of its constituent physical elements. These elements may be physical artifacts; people; the physical environment; or a combination thereof. For TEI, sensing usually incorporates several facets:

- *Presence:* often, TEI sensing begins with the question "is something present?" *Something* might be a physical object (in whole or part), a finger, hand, body, etc. Of particular interest are *changes* in presence – has something "appeared" or "disappeared." At a higher level of technical interpretation, such changes often lead to software *events*, such as entrance or exit events. TEI systems are also not always concerned with or capable of physically sensing presence – e.g., with an ambient display, where system activity may be associated with "virtual sensors" such as triggers within online space (e.g., the receipt of an email, change in state of an online service, etc.) In this interpretation of presence[2], any artifact is prospectively indistinguishable from each other. A determination of *which* particular object, person, etc. is present is the question of *identity*.
- *Identity:* in most cases, TEI sensing hinges not only on the presence of a physical entity, but also relative or absolute discernment of its identity. For example, RFID (radio frequency identification) tags, and more recently their NFC (near-field communication) tag variants, have been widely used within TEI systems for decades. Here, the determination of identity can be seen as matters of degree. E.g., some theft detection systems (in retail stores, libraries, etc.) monitor for (effectively) one-bit tags, monitoring the presence of a tag tuned to resonance within particular band of the electromagnetic spectrum. Such tags are sometimes referred to as "chipless RFID." This context concerns rudimentary discernment between tagged and untagged objects. Tags and readers tuned to different frequencies can avoid "false alarms" and support disparate uses.

  It is also common for RFID/NFC tags to establish "unique" identity, with (e.g.) 48-bit addresses comparable to the MAC hardware addresses of internet devices. In a middle ground, chipless RFID approaches provide several bits of identity, allowing discernment between (e.g.) 16 objects
- *Configuration:* beyond presence and identity, many sensing technologies are employed to monitor different forms of configurational status/state.
  - *Position:* the position of one or several physical artifacts (or of people's hands, heads, feet, etc.) are frequently sensed and mediated by tangible interfaces. Often, this positional data is within a two dimensional planar space (e.g., upon a table or wall). One dimensional (e.g., along a linear, circular, or more complex path) and three dimensional (e.g., of an artifact or body moved in freespace) positional sensing are also common.
  - *Orientation:* orientational sensing is also commonly sensed and interpreted within tangible interfaces. Sometimes this is in combination with 1D, 2D, or 3D positional information. Positional information is also sometimes interpreted in the absence of

[2] *Presence* as a term is also used within TEI in other important ways. In particular, as "a term derived from the shortening of the original 'telepresence,' [presence] is a phenomenon enabling people to interact with and feel connected to the world outside their physical bodies via technology."

positional information, as with the one-dimensional orientation of a knob. This knob might be mechanically fixed in place; or with presence/absence relative to some fixed locus (e.g., an NFC/RFID sensing location, perhaps in the context of a mechanical constraint such as a pin or well). While 1D orientational sensing is common in the absence of positional data, sensing orientation with three degrees of freedom (e.g., roll, pitch, and yaw) is frequently monitored in combination with 3D positional information (for a cumulative 6 degrees of freedom/DOF). Also, sometimes knob-like artifacts may have multiple degrees of orientational freedom, even along a common axis – e.g., when a knob-like artifact is pushed, or with the integration of several nested knobs (e.g. course and fine tuning).

- *State:* a great many other phenomena may be sensed, as we will elaborate below. This includes includes temperature, light, magnetic and/or electric fields, strain, flexure, and many others.

Agency and Proximity

Figure 5.1 differentiates between *passive* and *active* sensors, and further divides active sensors by degree. The technical definitions of passive active electronic components (from an electrical engineering perspective) extend beyond the scope of this book. Loosely expressed, while passive electronic components like resistors absorb energy in relatively straightforward ways, active components incorporate more internal complexity and are capable of expressing more complicated behaviors. This complexity, in turn, can be seen in varying degrees. For example, a transistor (prototypically a sandwich of three different materials, which can acts as an amplifier or switch) is regarded as an active component. So too are modern microprocessors incorporating millions or billions of transistors. In our loose, pragmatic consideration, we would regard transistors as being relatively simple active devices ("further to the left" of Figure 5.1), and microprocessors as relatively complex ones ("further to the right" of Figure 5.1).

Sensors may hold several positions/proximities relative to tangibles and/or people. They can be incorporated inside a tangibles, or upon a tangible's surface. We use the term "integral" to combine these two configurations (internal and dermal). They can also be near (proximal) or far (distal) from a tangible/person, without being in physical contact.

Contact-based sensors

An enormous breadth and variety of sensors exist, and continue to be created. As one indicator, one encyclopedia of sensors incorporates 10 volumes [Grimes et al. 2006]. Here, we present a brief survey of sensors as viewed from the perspective of tangible interfaces.

A sensor may be physically touching that which is being sensed, or not. The first category is referred to as *contact*-based sensors; the latter, *non-contact*. Perhaps the simplest and best-known form of contact-based sensor are switches and buttons. Several examples of these are illustrated in Figure 5.4a. Some of these incorporate a mechanical lever that extends the reach, increases the sensitivity, or otherwise transform how the switch is activated. These are often called "leaf switches." Switches can be "momentary" (automatically turning off when released), as with most keyboards; or of "alternate action" (stably toggling on or off, as with many power switches). Historically, switches have been largely electromechanical in nature, with moving physical internal parts. This has a variety of implications for their use as sensors, including "contact bounce"/"chatter," where the switch may quickly alternate between states for a short time (e.g., milliseconds), which must often be filtered out in software ("de-bounced"). There is also progressive movement toward "solid-state" switches, which may offer more stable binary/digital behavior (e.g., without requiring debounce measures).

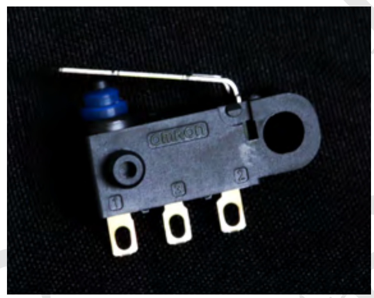


Figure 5.4 **electromechanical switches:** a) leaf switches; b) ad-hoc switches from BeatBearing [Bennett 2010]

Switches are traditionally manufactured devices, however, they may also be realized in many ad-hoc fashions. For example, Figure 5.4b illustrates a conductive steel ball bearing used to electrically bridge ("short circuit") between two adjacent metal surfaces, as utilized within the "Ball-Bearing Drum Machine" application by Peter Bennett[3]. This can be seen as a variation on the ball-in-cage tilt switch design (Figure 5.4c), with a rather reduced "cage."

Where switches typically transform mechanical contact into a ~binary on/off (contact/no-contact) response, a range of contact sensors provide an analog (variable/continuous) response to physical contact. Figures 5.5a (a force sensor) and 5.5c (a load cell/strain gauge) provide an analog response to varying physical pressure. In another variation, Figure 5.5b, a flex sensor, generates a varying resistance in response to progressive bend/deflection. Pressure sensors have been incorporated into various TEI systems including interactive tables [Marquardt et al. 2009] and floors [Augsten et al. 2010], sensor-rich clothes [Aigner et al. 2020], etc.

In general, force, flex, and load/strain sensors are all examples of analog devices (as are most sensors). Here, analog indicates the electrical signal varies continuously, rather than being constrained to (e.g.) the two-value configuration of an "on/off" binary device. As another

[3] https://www.technologyreview.com/2009/01/23/32495/a-ball-bearing-drum-machine/

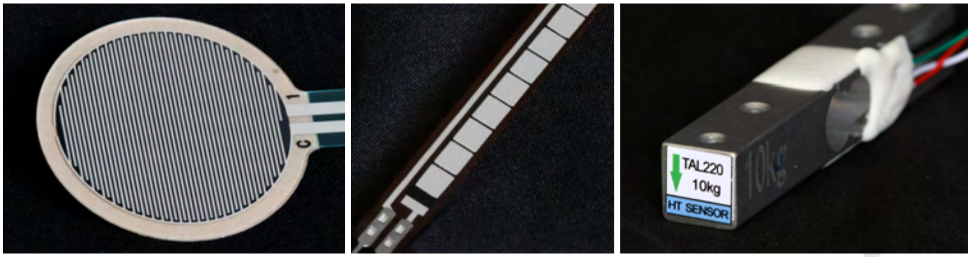


Figure 5.5 **force, flex, and load/strain:** a) force sensor; b) flex sensor; c) load cell/strain gauge.

example of an even more commonly used analog contact-based sensor, potentiometers are commonly used to measure the rotation or translation of some form of knob (Figure 5.6a,b).

Figure 5.6 **rotary potentiometer, linear potentiometer, and rotary shaft encoder**

Internally, potentiometers incorporate a variable resistors (also known as a voltage divider; Figure 5.7. For radial potentiometers, turned to one extreme, the potentiometer typically has minimal (near-zero) resistance; turned to the other, the nominal resistance of the potentiometer (e.g., 5kΩ – five thousand Ohms, the measure of electrical resistance). Sometimes this rotational range spans 360° (a single-turn "pot"); while multi-turn pots can rotate several times (with 3-20 revolutions being common). (Older analog radio tuners typically attached the tuning knob to a multi-turn pot.)

Potentiometers always have a "left-most" and "right-most" limiting position. In some tangible interface applications, this is undesirable. Here, a rotary shaft encoder (Figure 5.6) offers a common alternative, typically at a somewhat higher cost from both monetary and complexity perspectives.

Potentiometers and shaft encoders are frequently combined with both actuation and graphical displays. For example, linear potentiometers are sometimes integrated with motors (e.g., with actuated audio faders), while shaft encoders are frequently coupled to radial motors; and similarly, both with linear and radial LED arrays. Where motors and LEDs are active elements, passive springs are sometimes also integrated (e.g., with return-to-center devices). This passive actuation can have important semantic implications. For example, in David Small's awardwinning Talmud Project,a series of return-to-center potentiometer-backed knobs where used to explore a dense 3D textual space. With a console scaled to encourage single-user interaction, and single users having two hands, Small was able to focus his design efforts on the spaces reachable by simultaneous manipulations of at most two knobs, with reasonable confidence the remaining knobs where at their center positions.

As with the ball-bearing switch example, tangible interfaces often creatively employ elements in sensing roles that were not explicitly conceived as sensors per se. One example is the use of resistors (e.g., as in Figure 5.7a) as primitive ID tags. In the resistor case, a voltage divider circuit (Figure 5.7b) is often used in combination with an analog-to-digital converter. (Potentiometers such as Figure 5.6a-b also internally a voltage divider circuit.) Toward this, in Figure 5.7b, R_2 (the lower resistor) is selected at some reference value; where R_1 is the resistor ID. To consider a specific example, if the supply voltage (V_{in}) is 5V (a common value in digital circuits, and roughly the voltage of four AA batteries connected in series/succession), a reference resistance R_2 of 1kΩ is used, and a resistor "ID" R_1 of 1kΩ is chosen, the output voltage V_{out} would be 2.5V (thus dividing the input voltage by half). Most embedded computer platforms incorporate paths for sampling this voltage and mapping it to a digital number (say, 127, as half of the maximum value of an 8-bit unsigned integer/byte). In this example, if a larger resistor tag value is chosen, the V_{out} will be smaller, and vice versa, per the simple voltage divider ratio of $R_2/(R_1+R_2)$. As example uses, resistor tags were used in the first physical prototypes of the Marble Answering Machine and mediaBlocks [Polynor 1995a; Ullmer et al. 1998].

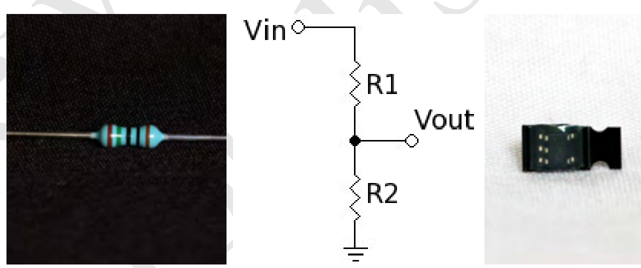


Figure 5.7 **Wired ID tag resources:** a) resistive tag (resistor acting as low-res ID); b) voltage divider circuit; c) digital serial number

While simple and (from some perspectives) a good starting point for first experiments, there are several complications with this approach. First, *if* a reliable electrical connection is made to the resistor tag, one might imagine discerning between a dozen or few tags. However, obtaining a reliable, minimal-resistance coupling to a given wired tag is often difficult (perhaps surprisingly so, for reasons that are difficulty to easily remedy). Secondly, if a "unique" ID is desired (in a world aspirationally populated by many tangibles, viewed from a world where computers and web pages are presently pervasive), the resistor approach does not scale, leaving sensors unable to distinguish even among a moderate numbers of tangibles.

One partial workaround to these challenges is the use of digital wired tags. For example, a "digital serial number" such as the One-Wire technology can provide a ~unique (48-bit) ID value, sometimes coupled with local digital storage, an onboard temperature sensor, and/or other functions. One-Wire digital serial numbers are somewhat more resilient against spurious electrical connectivity. This support can enable the use of (e.g., conductive velcro connectors; Figure 5.7c) to allow somewhat improved electrical connectivity, which would not be plausible with resistive tags. As one example, digital serial numbers and conductive velcro were used with later versions of mediaBlocks [Ullmer et al. 1998].

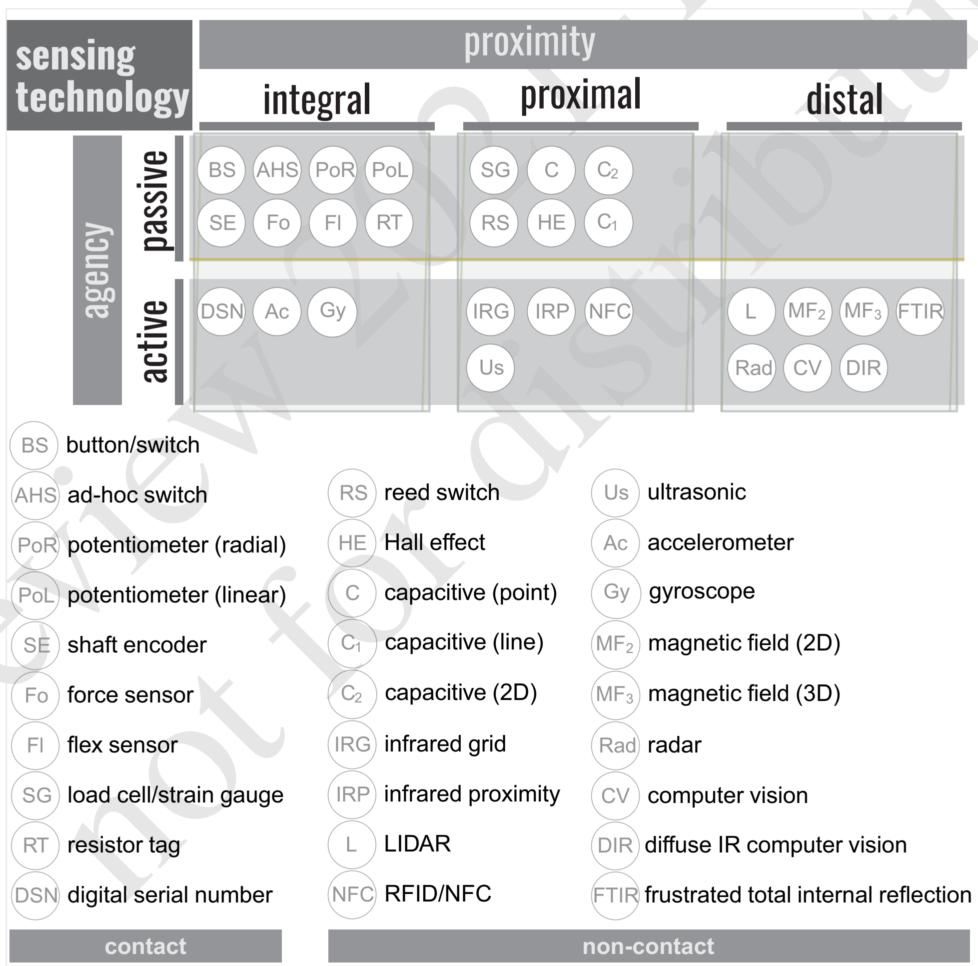


Figure 5.8 **Sensor technology design spectrum** (from Fig 5.1), viewed from sensor perspective

These contact-based sensors we have discussed can be viewed from within the context of Figure 5.1. Figure 5.8 expands on the first row of Figure 5.1, folding the two *agency* facets (active and passive) to the Y axis, so complementary sensor technologies can be compared with respect to each other. Here, buttons/switches BS, ad-hoc switches AHS, force sensors Fo, flex sensors Fl, shaft encoders SE, and radial and linear potentiometers PoR PoL are *integral* within tangibles, and *passive* with respect to their underlying sensor technology.

From a conceptual standpoint, the active/passive distinction is arguably less impactful and more subjective than with subsequent TEI mediation facets. As an example of subjectivity, within Figure 5.8, we indicate strain gauges SG as proximal. For the present, our rationale is that most TEI deployments thus far have integrated strain gauges within tables or floors, toward sensing tangibles placed upon or removed from their sensing surface (whether direct or mechanically coupled). That said, there is nothing specific to these sensors that requires this configuration; we regard it as historically descriptive, but not prescriptively constraining for future systems.

Contact-based sensing is widely used within tangible interfaces, and can be technically straightforward to implement. However, in practice, especially as a system begins to have more components – especially components that move – reliability and scalability often become problematic. In general, unless a system incorporates spring-like elements that remain under pressure, reliable electrical contact is difficult to maintain, often resulting in intermittent failures. Even for systems with electromechanical interconnects that are reliable as pairs, as larger numbers of physical elements are introduced, reliability issues often compound. E.g., in the Block system of Marks et al. [Anderson et al. 2000], designs that were highly reliable for a few tangible blocks experienced intermittent errors as the system expanded to dozens of blocks.

Non-contact sensors

For these reasons, the use of *non-contact* alternatives often supports more robust, reliable sensing within TEI systems. Historically, among the simplest and most common forms of non-contact sensing involves magnets in proximity of a *reed switch* (Figure 5.4.3a). One common place these are found is within window and door security systems (Figure 5.4.3b). Here, the magnet is typically embedded within the movable part of the window/door. When in close proximity to the magnet, the reed switch closes ("turns on"); away from the magnet, the reed switch re-opens ("turning off"). In the home/business security context, each reed switch can then be connected with long wires to some central controller, or relayed wirelessly through a radio transmitter. In similar fashion within tangible interfaces, a magnetic tag can be used to indicate the presence or absence of an artifact. Small constellations of magnets and reed switches can also be used to determine the class or identify of an artifact.

Web companion 5.1 (tech/figs/a1)

magnetic sensors: a) Plastic-encapsulated reed switch [photo via Brygg Ullmer]; b) magnet and reed switched used within a window security system [By SparkFun Electronics - CC BY 2.0 [a]]; c) 2D magnetic sensor grid used beneath tablet as an aggregate sensor[Liang et al. 2013].

[a] https://www.sparkfun.com/products/13247

Hall effect Where reed switches are electromechanical devices, *Hall effect sensors* are solid-state devices that can sense varying intensities of magnetic field. In addition to being used individually, 2D arrays of Hall effect sensors can be used to monitor the 2.5D position and strength of magnetic tags. Among other advantages, this allows the Hall effect array to be placed on (e.g.) the backside of a display screen/tablet/etc., and sense a magnetically tagged artifact on the other side. This is illustrated in Figure 5.4.3c [Liang et al. 2013].

Today, among the most common and best-known non-contact sensors are *capacitive sensors*. In simplest form, electrical *capacitors* can be seen as two conductive (typically metal) plates, separated by some non-conductive material (the *dielectric*). Thus assembled, the capacitor can "hold an (electrical) charge," depending upon the properties of the plates and the dielectric. One possible dielectric is air itself. Alternately, more than 50% of the mass of the adult human body is (salt) water [Watson et al. 1980] making the human body somewhat electrically conductive at low frequencies. When (e.g.) a finger or hand passes within an air-based dielectric, this can be capacitively sensed.

For tangible and embodied interaction, this effect can be realized with the simplest of sensors: a simple piece of wire. With the wire is attached to an embedded computer, one can first "charge" the wire (connecting it to a positive voltage). If the attachment is changed from an output to an input, the computer can monitor how long the wire takes to "discharge" below some threshold. The duration is impacted by the (close) proximity of the human body, thus allowing use as a touch or close-proximity sensor. This capacitive sensing can be realized for a single location/point; or in a matrix that allows 1D or 2D localization of one or multiple touches (multi-touch). In addition to traditional metal wires (e.g., copper), optically transparent conductors (e.g., indium-tin oxide, abbreviated ITO) as well as alternative materials and geometries[4], are used to realize 2D touch sensitivity upon dynamic graphical displays.

Web companion 5.2 (tech/figs/a2)

capacitive sensing: a) capacitive multitouch sensing on a dynamic graphical screen [By Willtron - Own work, CC SA 1.0, https://commons.wikimedia.org/w/index.php?curid=3381684]; b) the Book of Kells (~9th century illuminated manuscript) [Public Domain [a]], illustrating use of precious metals both as aesthetic and (prospectively) functional capacitive

[4] http://theconversation.com/touch-screens-why-a-new-transparent-conducting-material-is-sorely-needed-34703

element; c) a tangible supporting physical interactivity via touchscreen-based capacitive sensing [Voelker et al. 2015].

[a] https://commons.wikimedia.org/w/index.php?curid=44396

While capacitive sensing has come to widespread prominence in the 21st century, it holds implications for far older artifact. For example, one common definition of *illuminated manuscripts* (dating back more than 1,500 years) concerns the incorporation of metals (typically gold or silver) upon the page [Ullmer 2012b]. In this respect, at least relative to their design and materiality, both existing and novel illuminated manuscripts can be regarded as inspiring latent examples of capacitive touch sensors.

Where capacitive touchscreens are typically designed for sensing human contact, a substantial body of work has grown around using them to sense tangibles. Frequently, this takes the form of integrating capacitive touchpoints on a tangible. Variations here include metal (e.g., adhesive copper foil, as in Figure 5.4.3c); conductive epoxy;and electrically-conductive 3D printing filament [de Siqueira et al. 2018]. These conductive touchpoints are then electrically connected with an underyling touchscreen using a constellation of conductive pads that typically allows the tagged artifact to be registered as present, identified, and tracked. Here, the pads emulate fingertips, and frequently are fabricated with materials intended as the tips of capacitive styluses (e.g., conductive rubber or woven metal mesh).

Here, we have discussed active capacitive tracking of passive[5] fingertips and capacitively-tagged tokens. Sometimes, capacitive communications between two active devices are utilized, to simultaneously serve both as a sensing and communications medium. Such capacitive communication was used in the parameter bars of [Ullmer et al. 2003a] and between the four sides of Sifteo cubes [Merrill et al. 2012]. For example, with Sifteo, the establishment of active communications on one or multiple of the four edges also implies physical adjacency of a known sister Sifteo (with known identity and orientation). Conversely, the absence of communications on a given edge implies no detectable Sifteos are present along that face.

Capacitive sensing and communication is but one of many non-contact (“wireless”) sensing approaches. Another common approach, also with many variations, involves light. One of the simplest approaches is the use of one or multiple photoresistors. In some respects resembling potentiometers, photoresistors vary in resistance as a function of the intensity of light to which they are exposed. (Along related lines, photodiodes and phototransistors function in different ways but to similar end effect, offering more sensitivity, flexibility, and often smaller size, typically at the expense of higher cost and complexity.) This ability to detect changes in light can, if appropriately configured, be used to detect the presence or absence of a tangible. For instance, in the letter-matching puzzle the addition or removal of matching wooden letters (as constrained by the matching wooden constraint structure) – when used within a lighted space

[5] We discuss a possible variation on this assumption in our discussion of RFID/NFC technology.

– result in a corresponding change in sensed lighting. In this case, speech is used to express corresponding interactivity.

A more potent variation on optical sensing involves coupling a light detector with a light emitter. Sometimes these work in the visible spectrum. More often, infrared light – especially near-infrared light (just beyond the visible spectrum) – is used. The advantages of infrared are manifold, as we will slightly elaborate shortly. Among these are less visibility to human eyes, and less sensitivity to traditional mainstream inside illumination. The emitter and detector can be oriented toward each other, potentially interrupted by a leg, hand, object, or (e.g.) encoder ring[6]. Alternately, both emitter and detector can be oriented in the same direction, in pursuit of a reflection off some form of artifact (thus serving as an optical proximity sensors, as with Figure 5.4.3a). The emitter can also be steady in its illumination; or often modulated (e.g., turning off and on thousands of times per second), allowing greater distinction from ambient illumination. Such *optocouplers* were used in Chapter 1's 1976 Slot Machine, and continue within active use. Modulated infrared sources have also been used as localization beacons and communications mediums, dating at least to Xerox PARC's Active Badge applications [Want et al. 1992] (influential in their role within early ubiquitous computing systems [Weiser 1991a]).

When arrays of emitter/detector pairings are used, higher dimensional spaces can be monitored. For example, Figure 5.4.3b illustrates horizontal and vertical 1D arrays of infrared LEDs structured together with an array of detectors, all spanning a display screen. Here, one or multiple fingers or physical objects touching the screen occlude at least one horizontal and vertical optocoupler, allowing the physical stimulus to be localized.

Web companion 5.3 (tech/figs/a3)

infrared non-contact sensors: a) infrared proximity sensor; b) infrared 2D touchscreen sensor array; c) LIDAR unit for projection+detection of infrared structured light [by SparkFun Electronics - CC BY 2.0 [a]].

[a] https://www.sparkfun.com/products/14032

Where the use of one or several photoresistor/transistors or optocouplers can offer information across one or several points, the use of one, several, or numerous cameras, in concert with *computer vision* (CV), profoundly expands the range of the possible. Computer vision has existed as a resource for many decades. In recent decades, the increasing pervasiveness + performance (whether relative to resolution, sensitivity, dynamic range, and/or speed) and plummeting cost of cameras – perhaps in greatest part driven by smartphones – together with similar (if far greater) dynamics in computing capabilities (both in the field and the cloud) – have transformatively reshaped the shape and bounds of the possible.

[6] for example, quadrature phase encoders [Incremental encoder] are widely used

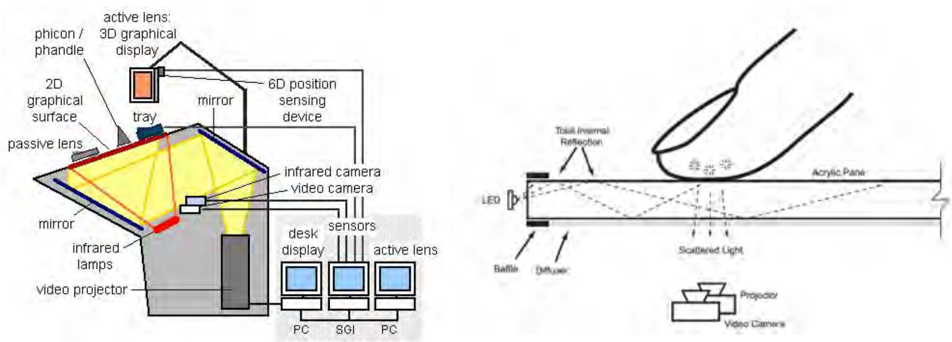


Figure 5.9 **computer vision:** a) Diffuse IR computer vision [Ullmer and Ishii 1997]; b) FTIR (frustrated total internal reflection) geometry [Han 2005b].

Many books and research careers have been dedicated to CV. In briefest survey, relative to tangible and embodied iteraction, CV can be regarded as having several facets.

- *computer(s):* Per our Figure 5.9, the computing underlying CV can be integral, proximal, or distal with the tangible interface itself; and relatively large or small in scale (be it physical size, computational capacity, power consumption, and number+kind of processors). The hardware of computing is also profoundly entangled with the software – be it built upon rich computer vision libraries or ad hoc in nature.
- *vision(s):* within CV, vision is often through one or many lenses, upon some form of optical sensor. These are typically composed of 2D arrays of *sensels* (the input-oriented inversion of pixels). Computer vision can also be applied to capacitive imaging, radar imaging, or other 1D, 2D, and higher dimensional fields.
- *light(s):* as with our distinction between photoresistors/transistors and optocouplers, illuminating light can be ambient (e.g., from the sun or artificial lights) or purpose-deployed (specifically tasked for computer vision); diffuse or structured (as in an arrays of projected points or lines, to assist the computer vision task); visible or invisible; and stable or varying (again, whether naturally or intentionally, as with a beacon or strobe), among other variants. The relatively near-field infrared structured light CV of the Microsoft Kinect, Apple True Depth (within the iPhone X), and HTC Vive; and far-field LIDAR (long in use within satellites, and achieving rapid growth in self-driving cars; Figure 5.4.3c), offer high-impact examples for the use of structured light. The target physical artifacts may be front-illuminated, rear-illuminated (as with the diffuse IR used in the metaDESK [Ullmer and Ishii 1997], HoloWall [Rekimoto et al. 1998], Microsoft Surface/Pixelsense, and reacTable [Jordà et al. 2007a]; Figure 5.9a), or side-illuminated (as with frustrated total internal reflection/FTIR [Kim et al. 2007]; Figure 5.9b).

- *thing(s):* again relative to tangible and embodied interaction, computer vision is most typically used to track things. These things may be people (hands, bodies, etc.), purpose-crafted tangibles, or diverse things large (meters, kilometers, ...) and small (mm, dm, ...). If the things are conceived in part or whole as tangibles for mediation with computer vision, then often (but not always) it is desirable to integrate some form of features that eases identification and tracking. This typically involves integration of one or multiple forms of optical fiducial markers (or more simply, fiducials or visual tags).

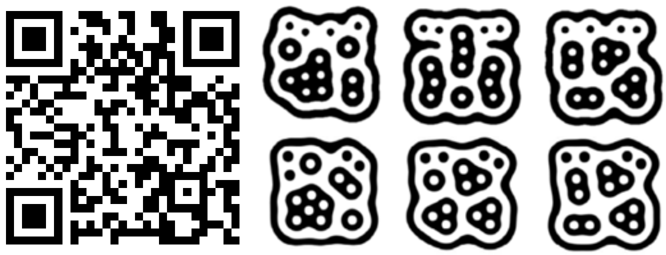


Figure 5.10 **Example fiducials for CV recognition:** a) QR code [Public Domain [7]]; b) ReacTIVision codes [Kaltenbrunner 2009a]

One common example are QR codes (Figure 5.10a). To the extent these can be identified within a TEI system, they illustrate an artificial marker specifically with the purpose of digital identification. As noted, in practice, QR codes presently have several limitations for TEI. In their modestly high-resolution form, they are not always easily detected or parsed when they are small, at an angle, and potentially moving within the visual scene. Also, while legible to machines, they often lack legibility or aesthetics to human eyes.

Visual fiducials that are presently more common within TEI systems include ReacTIVision tags [Kaltenbrunner and Bencina 2007a] (introduced along with the ReacTable profiled in Chapter 1) and AR toolkit (Figures 5.10b,c). Additional special classes of fiducials include small visual glyphs such as Anoto (typically identified by augmented pens [Signer and Norrie 2007]) and neARtracker, used with modified (and often legacy) smartphones [Coconu and Hege 2017; Coconu et al. 2018]; infrared printed tags, as within the cards of Lord of Vermillion[8]; and retroreflective patterns or markers [Underkoffler et al. 1999]. These latter approaches hold the advantage of reducing visual clutter and (correspondingly) accomodating both more and less control of the visual field. Retroreflective tags – whether in the visible spectrum like Urp [Underkoffler et al. 1999], or infrared such as Vicon and OptiTrack – also hold the advantage of tolerating more lighting variability, teasing apart fiducials from background imagery, and (somewhat correspondingly) allowing high-precision tracking.

[8] https://www.reddit.com/r/electronics/comments/1zifgz/how_do_these_japanese_arcade_table_games_work/, http://kanryuhobby.blog58.fc2.com/blog-category-25.html

Figure 5.11 **RFID/NFC sensors:** a) Grove/seeed [photo courtesy Brygg Ullmer]; b) music bottles (analog + digital tags); c) Microsoft Zanzibar NFC + multitouch sensing 2D array sensor

As mentioned, while CV has been most frequently employed with optical technologies, it has broader applications. We have mentioned CV for magnetic imaging arrays. Radio (especially radar) and acoustic (especially sonar) imaging have also experienced widespread use. As with optical imaging, radar and sonar imaging can be of a single point (e.g., binary or analog proximity detection), or of 1D, 2D, and higher dimensional arrays. TEI applications of radar date to at least Paradiso et al.'s "magic carpet" prototypes [Paradiso et al. 1997], sensing the movement of human bodies with low-wattage Doppler radar at the ~15' (4.5m) scale. More recent examples include Google ATP and Infineon's Project Soli, which reduces the radar unit size to centimeter scale, with the potential for sensing millimeter-scale hand gestures and the physical state of other artifacts.

With such radar typically operating at the low-GHz range of the electromagnetic spectrum, this makes it a "near neighbor" of mobile telephony, WiFi, Bluetooth, GPS, and many other communications technologies. Some of these sister spectrum technologies also have strong sensing implications. GPS is perhaps the most obvious example, albeit best suited for localization with meter-scale granularity in outside applications. Bluetooth, and more specifically its "low energy" (BLE) variants, also offer position-tracking capabilities.

Sensor fusion and actuated sensing

While the above discussion has centered on individual sensing technologies, there are often benefits from combining multiple sensing technologies, sensing and display technologies, and/or sensing and actuation technologies.

As one early example, the metaDESK combined three sensing technologies: diffuse infrared computer vision; passive resistive tags; and 6DOF magnetic field sensing [Ullmer and Ishii 1997]. There, computer vision allowed tracking the 2D position and orientation of multiple tangibles upon the desk. However, as implemented, computer vision could not distinguish between objects, nor track them in 3D. Instead, object identity was implicitly/heuristically estimated by the combination of electronic tags (which, implemented later, would have used

RFID or NFC tags) and computer vision. Magnetic field sensing was used to track the 2D passive lens and 3D active lens; but at considerable (several thousand dollar) cost per sensor, and with wired sensors.

In this example, sensor fusion was used to achieve hybrid capabilities that no individual technology could then achieve. In a more recent example, Microsoft Zanzibar interweaves a 2D array of NFC sensing antenna with a 2D array of capacitive sensing elements. Sensor fusion can also realize other benefits. For example, RFID/NFC is often relatively energy intensive. If, in an example analogous to Zanzibar, one or many magnetic reed switches or Hall effect sensors are combined with RFID/NFC readers, the RFID/NFC antenna can be energized only when magnetically-sensed updates are sensed. In this fashion, energy consumption can be dramatically lowered, sensor costs decreased, and sensing resolutions increased, at the cost of increased system complexity.

In addition to multi-sensor fusion, sensors and displays can be creatively combined to yield new or higher-fidelity capabilities. For example, "structured light" typically combines of visible or invisible projection with computer vision or other optical elements. In one variation, one or multiple visible or infrared grids are projected into the world. Strategicaly aligned camera sensing of these grids is used to correlate deformations in the projected pattern with 3D spatial positions. In notable commercial examples, both the Microsoft Kinect and Apple TrueDepth (e.g., within the iPhone X) rely upon the projection of constellations of low-intensity infrared dots.

Many alternate variations of structured light are possible. For instance, in one mode of operation, in 2020, the TI LightCrafter projector modulates *each pixel* up to 9,523 Hz with binary patterns, or up to 247 Hz with 8-bit grayscale patterns. This allows each projected pixel to broadcast a location or other data to tangibles, robots, etc. within the field. This has been used compellingly toward tangibles in [Le Goc et al. 2016].

Another variation is actuated sensing. In an early variant, mobile robots have been used to adaptively relocate sensors within a larger volume [Singh et al. 2006]. In a variation novel to this book, in the Appendix, we show several systems where one or multiple NFC/RFID readers (potentially in a sensor fusion configuration with Hall effect magnetic sensors or other elements) are rotated or translated through a larger volume. This is partially reminiscent of electromechanical hard disk drives, where the combination of a spinning platter and actuated arm tipped with a sensor is used to physically access large quantities of digital information. Such an approach, applied to NFC sensing, can also leverage decades of algorithms in hard disk seek optimization. For some scenarios, such as illustrated in Figure A.7 and partially elaborated in the Appendix, such actuated sensing approaches can offer relatively low-cost, flexible realization of tangible tracking technologies.

Figure 5.12 **Hextok rotary workspace** (illustration courtesy Brygg Ullmer)

Displays and actuation

Without sensing, the realms of computing are left blind to physicality, and particularly to human interactions within the physical world. In a similar vein, displays and actuation are the paths by which people gain vantages within tangibles and into the cloud – to observing and engaging the computational mediations underlying TEI.

We first consider agency and proximity in display and actuation contexts (Figure 5.1). We then survey display and actuation technologies of particular relevance to TEI.

Agency and proximity

As with sensing, while there exist theoretically rigorous interpretations of passive vs. active agency from electrical engineering perspectives, we briefly consider an interpretation of relevance to broader audiences. Most flat-panel displays (whether LCD, LED, plasma, etc.) are examples of active devices. In a simple illustration, if power is removed, the visual display disappears. One interpretation of a passive display would be a printed visual element (whether by hand, inkjet or laser printer, 3D printer or router, etc.). Electronic ink/paper offer a more ambiguous example. When mid-update and/or backlit, e-ink has the properties of an active display device. Alternately, when power is removed, e-ink displays typically retain their last state (and thus are regarded as bistable). This second, non-powered e-ink state may reasonable be viewed as passive in nature.

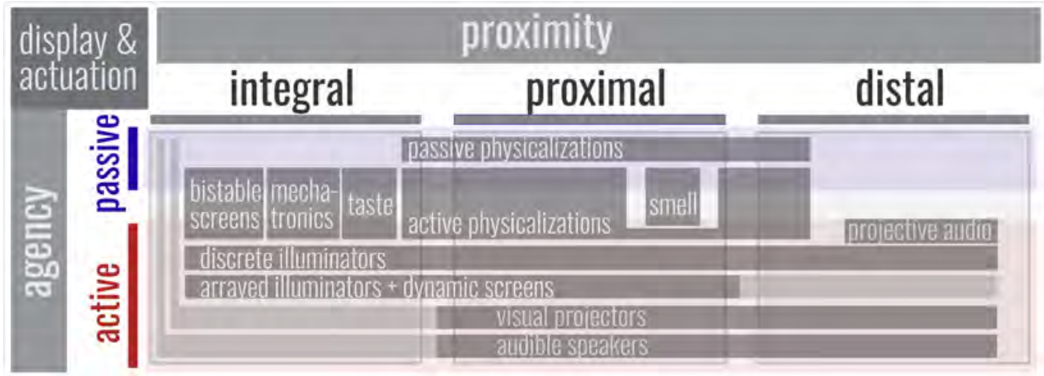


Figure 5.13 **TEI design spectrum for display and actuation technologies**

For actuated systems, additional nuances between active and passive exist. An electric motor (available in dozens of different forms) is a classic example of an active device. However, if power is removed, even the simplest rotary or linear motor frequently acts as a passive mechanical constraint. In another example, some particle brakes (as a particular kind of electromagnetic brake) with integrated controllers offer haptic mediation of mechanical detents, etc. These can be regarded as including both active and passive (resistive/dissipative) facets. In another variation, systems of levers, gears, pulleys, springs, and other forms of mechanical constraint are frequently present within TEI systems. These generally are passive in nature; though are frequently combined with active elements (e.g., solenoids or servomotors).

As with sensors, displays and actuation can be integral, proximal, or distal to the tangibles they mediate. For "active tangibles" with embedded displays or actuators, the technology is integral. If a tangible sits atop (e.g.) a mediating graphical display, or upon a surface using vibration or magnetism to actuate tangibles, the relationship is proximal. Often the distinction between proximal and distal can be subjective and a matter of degree. For example, when a graphical projector (for European readers, beamer) is used to projectively illuminate a tangible workspace, is this proximal or distal? A picoprojector used in a Luxo armature mount from a 1m distance might be regarded as proximal, with a ceiling-mounted projector as distal; but this distinction is likely best regarded as a gradient and matters of degree.

Displays

In this section, we will briefly survey visible, auditory/acoustic, thermal, and olfactory displays. These modalities do not (necessarily) involve direct physical contact. In the next section, we will consider modalities that do involve direct physical contact, including tactile/haptic, gustatory, and mechatronic actuation.

Visible displays

Technology-mediated displays of information date long into prehistory. One could consider an ~artificial source of light as among the simplest “active displays.” For example, the Lighthouse (Pharos) of Alexandria, one of the Seven Wonders of the Ancient World, dates to before 250 BCE (Figure 5.6.1a). As an early example of information-sensitive signaling, Longfellow’s “Paul Revere’s Ride” (1860), a well-known poem in American literature recounted an 1775 event in the American War of Independence. This included the lines:

> If the British march
> By land or sea from the town to-night,
> *Hang a lantern aloft* in the belfry-arch
> Of the North-Church-tower, as a signal-light, –
> *One if by land, and two if by sea....*

Here, silversmith Paul Revere needed to recognize and parse this active visual information indicator; but this “legibility” was not to extent to the hostile British forces (Figure 5.6.1b).

Web companion 5.4 (tech/figs/a4)

Early active visual signaling: *a) Lighthouse (Pharos) of Alexandria, ~250 BCE [By Hermann Thiersch - Public Domain [a]]; b) Old North Church and Paul Revere sculpture, ~1775 - By Onyo at wts wikivoyage, CC BY-SA 4.0 [b]; c) Signalling with Heliograph at Alaska-Canada Border, ~1910 - By US National Oceanic and Atmospheric Administration - Public Domain [c]; d) Old John Hancock Building, weather + baseball beacon, ~2013. By Eric Kilby - CC BY-SA 2.0[d]*

[a] https://commons.wikimedia.org/w/index.php?curid=42458833
[b] https://commons.wikimedia.org/w/index.php?curid=22845890
[c] https://commons.wikimedia.org/w/index.php?curid=95902
[d] https://www.flickr.com/photos/ekilby/8797263134

Active technology-mediated visual communications made key progress in the 1880s with the commercial release of incandescent electric lighting (Figure 5.14a). By World War I, electric signal lamps were used for military communications (Figure 5.6.1c). Electric traffic lights began to enter use in the same timeframe (Figure 5.6.1d). In a Boston-area civilian context, a visual weather beacon at the top of the 36-story Old John Hancock Building, was used from 1950 onward to communicate the weather:

> Steady blue, clear view
> Flashing blue, clouds due
> Steady red, storms ahead
> Flashing red, snow instead[9] (Figure 5.6.1e)

[9] https://www.americaninno.com/boston/what-is-the-rhyme-for-deciphering-the-weather-lights-on-the-old-hancock-building-in-b

"During baseball season, a flashing red means that the Red Sox game has been cancelled due to weather conditions[10]." The Hancock weather beacon can be considered an early civilian example of an ambient display: the active communication of abstract information via a physically-situated, human-legible display.

In Figure 5.14, we visually illustrate a variety of point sources of active artificial illumination. Incandescent (Figure 5.14a) and neon (5.14b) are the oldest of these. While requiring more electrical current than can be provided directly by output lines of embedded microprocessors, they can be indirectly controlled via (e.g.) solid state relays and power transistors.

The nature of both visual indicators and lighting at large has dramatically transformed thanks largely to light-emitting diodes (LEDs). Red LEDs first reached economical commercial viability in the late 1960s. Red and (later) green LEDs were followed by blue and white LEDs in the 1990s, reaching light levels suitable for illumination in the early 2000s [Cho et al. 2017].

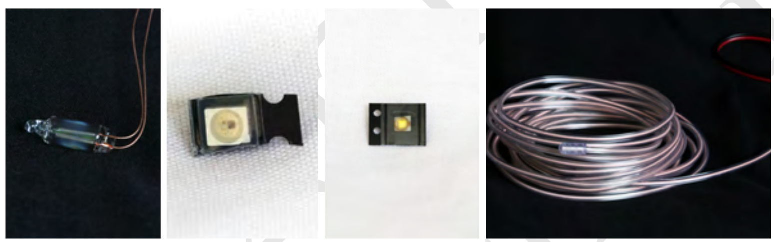


Figure 5.14 **Discrete illumination variants:** *a) incandescent electric light - Public Domain [11]; b) neon light (photo courtesy Brygg Ullmer); c) classical LED (photo courtesy Brygg Ullmer); d) electronically-addressable LED (photo courtesy Brygg Ullmer); e) electroluminescent (EL) wire (photo courtesy Brygg Ullmer)*

LED illumination can be digitally controlled as an information display in several fashions. First, the brightness of conventional fixed-color LEDs can be controlled through a technique called pulse-width modulation (PWM). Here, the LED is rapidly cycled on and off, typically with frequencies in the kHz range[12]. The level of brightness can be controlled by varying the fraction of time the waveform is maintained at the supply-level vs. ground-level state. Many microcontrollers include hardware PWM support, allowing this modulation to be conducted "in the background," without continually consuming computational resources.

An increasing fraction of LEDs are both electronically addressable, and host multiple internal LEDs of different color spectrums. The electronic addressing aspect allows multiple LEDs – whether 10 or 10 million – to be controlled over a shared address and/or data lines (rather than each requiring independent wiring). The incorporation of red, green, blue, and

[10] http://www.celebrateboston.com/strange/weather-beacon.htm

[12] https://www.digikey.com/en/articles/techzone/2016/oct/how-to-dim-an-led-without-compromising-light-quality

(sometimes) white LED subelements allows the full color spectrum to be synthesized (from the perception of human color perception).

In addition to LEDs, other discrete sources of digitally-controllable illumination exist. For example, electroluminescent (EL) wire and film (Figure 5.14f-g) are available in many colors, and can provide shaped illumination across large fields with modest power consumption.

These individual points, lines, or fields of illumination can be employed in TEI systems directly, or as backlights or illuminators for textual or visual displays. Resonant with the "strength in numbers" meme, it is also frequently desirable to integrate and control multiple illuminated visual elements. Several approaches are illustrated in Figure 5.6.1.

Web companion 5.5 (tech/figs/a5)

Ganged illumination variants: *a) Nixie tubes – By Christian D Fielding - Own work, CC BY-SA 4.0*[a]*; b) Flexible LED Matrix – By SparkFun - CC BY 2.0*[b]*; c) NeoPixel Stick – By SparkFun - CC BY 2.0*[c]*; d) NeoPixel Ring – By SparkFun - CC BY 2.0*[d]

[a] https://commons.wikimedia.org/w/index.php?curid=75348769

[b] https://www.sparkfun.com/products/13304

[c] https://www.sparkfun.com/products/12661

[d] https://www.sparkfun.com/products/12665

In the first of these, the Nixie tube (Figure 5.6.1a) (dating to the 1950s) provides an example of multiple symbols/glyphs selectively illuminated within a single discrete component. More common today is a pixelated approach of LEDs or other "native-digital"picture elements (pixels). For example, regular 1D and 2D arrays such as the "matrix," "stick," and "ring" of addressable full-spectrum LEDs of Figure 5.6.1b-d. These LED structures may in turn be arrayed in larger 1D, 2D, or 3D arrays and constellations. E.g., the curved large-scale media facade of Figure 5.6.1b illustrates how many strips or sheets of LEDs can be arrayed.

Web companion 5.6 (tech/figs/a6)

Small and large pixelated displays: *a) pixelated displays integrated within keyboard keys – By Kars Alfrink - CC BY 2.0*[a]*; b, c) different approaches to curved media façades – Times Square Billboard By JBuechler, CC BY-SA 3.0*[b] *and Iluma Mall screen façade designed by WOHA in Singapore By William Cho, CC BY-SA2.0* [c]

[a] https://www.flickr.com/photos/kaeru/26518087/in/photolist-6byKDh-6byKtS-8MzhT-81RMjV-81UVrm-3kUUp-4DWjK3-5qPjYU-6buBKK-4jjBg1-5droMn-4jjNg7-5dri72-4VAXW8-bWzgc7-6rYAtZ-4WUJ92-7T7U2v-5LjxT6-9r69nE-5fuuzx

[b] https://commons.wikimedia.org/w/index.php?curid=6893402

[c] https://www.flickr.com/photos/adforce1/4632695586/in/photolist-84nLZQ-df6Rdr-fgx2JB-6e5q97-784ziB-81xcn8-81xcsZ-81Amvd-81xcp8-81xcnT-81xcqg-8emkFr-fgwXSz-7k9Q8R-6RUft1-6RU71E-djtExw-6RHYyi-81xckF-81Amt7-81xcrz-81AmCf-7JwE56-7kdK9d-6vX5nc-84TMxU-7CABDP-7CAw1R-cDqdGy-6wispN-6weeUF-6wedNT-a87YJj-6wehpV-7k9R5D-7q2GKp-aScUrF-aHsDNn-7kdKeQ-aHsEPF-aHsCFV-fgx1ce-9QKeJ2-7CAysp-7CEjUj-7CEtt1-7CEniq-7CEshW-7CAD8X-7CAuqM

While the LED structures of Figure 5.6.1 each integrate tens of illuminated pixels, most common today are graphical screens integrating millions of pixels. Today, these are most common at physical scales ranging from ~10cm to ~10m diagonal in smartphones, tablets, laptops, and large rectangular displays. They are also growing more common at smaller and larger scales. E.g., Figure 5.6.1a shows a subset of a keyboard where each key incorporates a dynamic graphical display. At a larger scale, Figures 5.6.1b-c illustrate different approaches to curved building-scale media façades. In the realm of interactivity, large physical scales raise many unanswered questions, which hold strong potential for creative TEI engagement.

Our discussion of capacitive and infrared sensing began to discuss integrations of displays with multitouch interactivity (Figure 5.4.3a, 5.15a). In some cases, as with the innovative SUR40 PixelSense product from Microsoft and Samsung, both infrared-sensitive sensels and pixels are co-resident on the same mediating surface. In others, as with MultiTaction, arbitrarily large arrays of modular infrared Integrated Backlight Emitter Camera (IBEC) modules allow Computer Vision Through Screen (CVTS) toward recognizing fingertips, fingers, hands, and objects[13].

Another technology innovation with strong TEI implications are organic LEDs (OLEDs), including flexible OLEDs (FOLEDs; Figure 5.15b) and transparent OLEDs (TOLEDs; Figure 5.15c). At present, the majority of pixel displays combine an absorbtive liquid crystal display (LCD) layer with a backlight. Older backlights were typically fluorescent, electroluminescent (EL), or (in the case of projectors) halogen. Newer backlights are more often LED, whether as a uniform luminous field, or capable of addressing subregions. (The latter approach allows higher contrast and dynamic range, and lower energy consumption, by dimming or extinguishing the backlight behind regions of black or darker colors.)

Figure 5.15 **Pixelated display variants:** *a) multitouch and object-sensitive tabletop display (photo courtesy of Orit Shaer); b) ClearBoard: transparent OLED display [Ishii et al. 1994]*

With OLED, FOLED, and TOLED displays, organic electronic elements are printed onto varied underlying substrates. This printing process may involve masks, inkjets, or direct 3D

[13] http://multitouch.s3.amazonaws.com/downloads/products/product_multitaction55inch_111011-A4-web.pdf

printing of OLED elements[14]. The interactive potentials of these new mediums have driven the subfield of organic interfaces [Akaoka et al. 2010; Coelho et al. 2009; Holman and Vertegaal 2008; Lahey et al. 2011], often highlighting foldable interactive structures [Gallant et al. 2008].

Another major class interactive pixelated displays are the use of graphical projectors/beamers for projective illumination (Figure 5.16). These have a long history within TEI, including the early 1990s DigitalDesk system of Wellner, Mackay, et al. [Wellner 1993a]; the mid-1990s back-projected and -sensed metaDESK [Ullmer and Ishii 1997]; and the Urp system introduced in Chapter 1 [Underkoffler et al. 1999]. Several illustrative projector technologies are illustrated in Figure 5.16.

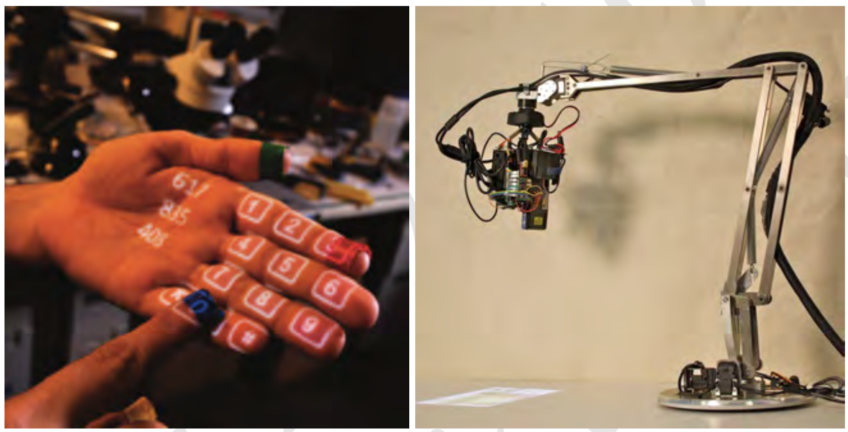


Figure 5.16 **Projective illumination variants:** a) SixthSense (body-based; courtesy MIT Media Lab); b) LuminAR (armature-based; courtesy MIT Media Lab).

Projective display technology extrapolations

As with many areas of technology, dramatic projective display technology advances are rapidly transforming the shape of the possible. We next consider some of these implications. Similar trends and extrapolations could be made with flat-panel display technology, spatial imaging technology, and others. Our considerations are intended to be illustrative, and our methods partially generalizing to these other mediating technology regimes. First, we briefly consider three envisionments of scaled-up projective mediation within room-scale spaces, as forward-looking toward a future of intensively mediated spaces (Figure 5.17).

White Room, Luminous Room, and Office of the Future

Michael Naimark's "White Room" art project explored the capture and projective remediation of spaces (Figure 5.17a; [Naimark 1984, 2005]). There, a video camera recorded a domestic

[14] https://www.oled-info.com/oled-inkjet-printing,
https://www.graphene-info.com/graphene-3d-lab-files-patent-3d-printer-can-print-graphene-based-oled

space, while sitting on an activated rotary platform. All surfaces of a domestic space – couch, table, paintings, walls, and floors – were then painted white. Finally, the slowly spinning camera was replaced with a projector, with playback begun in angular synchrony. While Naimark used a single projector, his concept generalized far more ambitiously:

> The image source may be a remote video camera or it may be from a computer database.... A relationship exists between display and interactivity. Consider filling all surfaces of a media room with imagery... [Naimark 1984]

In a related spirit, while we have discussed Underkoffler et al.'s "Urp" urban planning example in Chapter 1, this was one of a larger family of demonstrations of his "luminous room" and "I/O bulb" concepts [Underkoffler et al. 1999]. As illustrated in Figure 5.17b-c, these explore replacing all artificial lighting in built spaces with bidirection, pixelated lighting. The parallel "Office of the Future" work by Raskar et al. [Raskar et al. 1998] included an illustration depicting one possible consequence and variation of such an approach (Figure 5.17d).

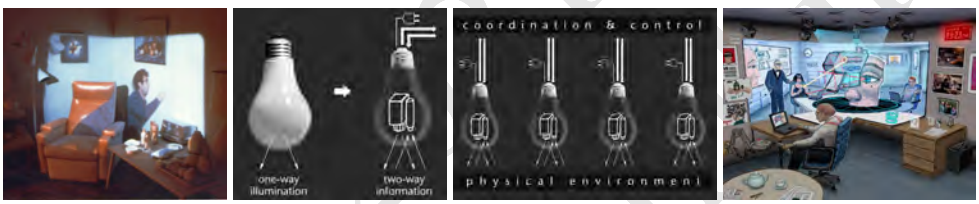


Figure 5.17 **Room-scale projective (re)mediation:** a) Naimark's White Room [Naimark 1984, 2005] (Photo courtesy Michael Naimark); b-c) Underkoffler et al., Luminous Room [Underkoffler et al. 1999]; d) Raskar et al., "Office of the Future" [Raskar et al. 1998]

Projective technologies, by the numbers

These visions are well-complemented by numerical grounding relating to projection technology. As a first point of comparison and reference, the metaDESK [Ishii and Ullmer 1997a; Ullmer and Ishii 1997] integrated the (then newly-released) Barco 808 three-tube CRT projector. This offered a dramatic increase in resolution (1280×1024) and brightness over the LCD-technology predecessor (640×480) used within the earlier-generation VisionMaker prototype used within Fitzmaurice, Ishii, and Buxton's "Bricks" system [Fitzmaurice et al. 1995a].

Figure 5.18 compares the 1996 Barco 808 with a series of 2018 projection technologies, as well as several extrapolations in the 2040 timeframe. The 1996 price of the Barco 808 (ca. US$25,000) is converted to 2018 USD for comparison. In addition to absolute metrics of brightness, resolution, weight, etc., multiplicative comparisons are made, with larger numbers generally being desirable. (Note that the decibel (dB) metric of loudness is logarithmic.)

Our purpose in assembling Figure 5.18 is severalfold. First, it is clear that there has been an enormous progress in projector technology in recent decades. In attempting to match the

Barco 808 with 2018-vintage projectors of comparable brightness and resolution, projector #3 (AAXA ST200) is among the closer candidates. For comparable performance,

- the cost decreased by a factor of 75×;
- the weight decreased by a factor of 215×;
- the size decreased by a factor of 575×; and
- the wattage (power consumption) decreased by a factor of 25×.

Many of these facets continue to improve exponentially, driven especially by increases in brightness, and decreases in price and wattage, in white LED technology [Cho et al. 2017].

	name	year	weight	×	size	×	resolution	×	watts	×	lumens	×	US$	×	dB	×	contrast
	Barco 808	1996	150lb (67kg)		230L		1280×1024	##	500		150		41,000		41		
1	Philips PicoPix PPX4350W		.28lb (.13kg)		0.1L	2300	640×360	0.2		0.0	50	0.3	350		28		
2	Anker Nebula Capsule	2018	.94lb (.4kg)	160	0.5L	460	854×480	0.2		0.0	100	0.7	350	117	30	3.5	400:1
3	AAXA ST200		.7lb (.3kg)	214	0.4L	575	1280×720	0.7	20	25.0	150	1.0	550	75			
4	Panasonic PT-AE7000U						1920×1080	1.6		0.0	3,000	20.0	3,100	13	22	8.9	
5	Sony VPL-VW285ES		28lb (13kg)		87L	2.6	3840×2160	6.4	350	0.7	1,500	10.0	5,000	8	26	5.6	
6	Sony VPL-GTZ1						4096×2160	6.8		0.0	2,000	13.3	35,000	1.2	26	5.6	
7	Panasonic PT-RZ31KU		174lb (79kg)	0.9	383L	0.6	1900×1200	1.8	2,870	5.7	31,000	206.7	95,000	0.4	49	0.4	20,000:1
8	Barco XDL-4K75		520lb (236kg)	0.3	759L	0.3	4096×2160	6.8	9,700	19.4	75,000	500.0	364,000	0.1			
5*	Naïve extrapolation	2040	.13lb (.06kg)		0.2L		3840×2160		14		2,000		67				
7*	Naïve extrapolation	2040	.8lb (.06kg)		0.7L		1900×1200		115		31,000		1,200				

Figure 5.18 **Projection system comparison:** Several different performative specifications of 2018-vintage projection products are compared with the Barco 808 projector used within the 1996 metaDESK system [Ishii and Ullmer 1997a; Ullmer and Ishii 1997]

Second, there are many different combinations of price, size, performance, and power consumption, spanning many orders of magnitude. As one example, the two most expensive 2018-vintage laser-based projectors we consider have lumen (brightness) outputs of 31,000 and 75,000 lumens. These units are billed as "large venue" projectors. For example, a July 2017 press release describes projective illumination of the Walt Disney Concert Hall (Los Angeles) with projector #7:

> ...front projection on a [large building] façade typically cannot be seen until sunset or shortly thereafter.... But [with two 31,000 lumen projectors] we saw pictures on the concert hall at 6pm with a blue sky behind the building. [15]

Third, while impossible to project with precision, naïve extrapolations of the ratios allow order-magnitude contemplations of the ballpark performance that might be anticipable in (e.g.) 2040. If we were to extrapolate comparable evolutions in (e.g.) cost, weight, size, and wattage relative to the capabilities of projector #5 through 2040, this would suggest a 4K-resolution projector of comparable size, weight, and wattage – and within order magnitude, cost – of a 2018-vintage spotlight bulb. Such bulbs would be closely resonant with the envisionments by Naimark, Underkoffler, Raskar, et al. described above (Figure 5.17). Similarly, a simplistic extrapolation of the "large venue" projector #7 could suggest comparable illumination (and likely far higher resolution) to deployments the size, cost, and pervasiveness of 2018-vintage street lights and large building floodlamps, with all the mediating powers and potentials of computational illumination.

These passages from ∼1990s envisionments to ∼2040s ubiquity (if not far sooner) This also represents a common time evolution for revolutionary technologies: the four- to five-decade passage from (e.g.) Vannevar Bush's 1945 Memex hypertext envisionment [Bush 1945] to the mid-1990s explosion of the web; or from Ivan Sutherland's "Sword of Damocles" head-mounted display (HMD) [Sutherland 1965] to the (e.g.) 2016 release of the Oculus Rift HMD.

Audible displays

While a majority of TEI systems have utilized visible displays, many other modalities hold strong potential. As noted, among the most popular TEI systems have involved performance and engagement with music. Also, in the late 2010s, AI-backed speech recognition and synthesis continues an explosion in deployment, perhaps especially amidst smart devices (many synergistic with or exemplary of TEI artifacts). Both music and speech point to the criticality of audible displays.

Per Figure 5.1, the source(s) of audio within TEI can be integral, proximal, or distal. Figures 5.1a-b illustrate smaller and larger piezoelectric transducers that are commonly integrated within electronic devices. Conversely, 5.1c-d picture parabolic and ultrasonic directional speakers, which can sculpt the soundfield in proximal and distal configurations.

Audible displays can also be both active and passive in nature. Work such as [Ishiguro and Poupyrev 2014] creates aesthetic 3D printed interactive structures that act as speaker elements. While the underlying speaker transducers are active, the acoustics are strongly shaped from purpose-fabricated passive materials.

[15] https://na.panasonic.com/us/us/case-study/worldstage-got-premier-party

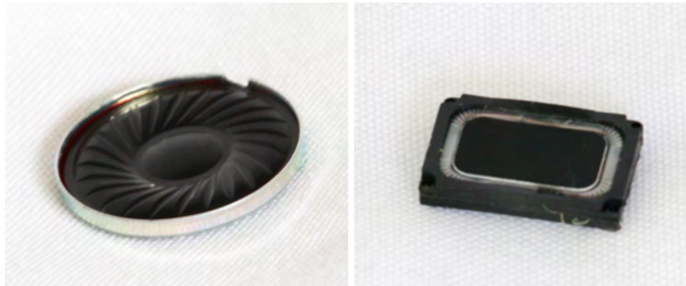


Figure 5.19 **Speaker technology examples:** a) piezoelectric speaker element (photo courtesy Brygg Ullmer); b) piezoelectric rectangular speaker (photo courtesy Brygg Ullmer)

Olfactory displays

While less common than visual and audible displays, olfactory displays – the chemoreception underlying our sense of small – has a long history, with growing research activity [Yanagida 2012] and practical deployments. While not explicitly incorporating computation, Heilig's 1962 "Sensorama" platform is well-known for incorporating odor emitters along with its stereoscopic visible display, stereo sound, fans, and motion chair [Heilig 1998, 1962]. Modern examples include both personal, near-proximal examples, as illustrated in Figure 5.6.4; as well as more distal examples.

Web companion 5.7 (tech/figs/a7)

Olfactory technology examples: a) wearable on-face olfactory display "nose" prototype [Wang et al. 2020]; b) another proximal distal fan-driven olfactory display [Pornpanomchai et al. 2009].

Actuation

For computational models to be synchronously mediated with the physical world, a growing number of TEI practitioners feel the actuation of tangibles – the ability of artifacts to move – to be critically important. Actuation can be expressed in a number of physical dimensions. These include:

- 0D: vibration often does not involve an externally observable movement, yet can be a powerful mediating technology. The source can be an electromechanical vibrator (often a miniature motor spinning an off-axis weight); or electrovibration, where the perception of vibration is electrically induced [Bau and Poupyrev 2012; Bau et al. 2010]. This can involve a single vibratory point (as presently ubiquitous in smartphones and smartwatches); or an array of points, as has been explored in belts and vests that (e.g.) allow the wearer to feel the orientation of a compass or proximal events.

- 1D: actuation can move in a single physical dimension, be it translational or rotational. Common examples involve the rotation or translation of a mechanical element via AC or DC motor; stepper motor; servomotor; or electrostatic motor. One such electromechanical element can be actuated; or a 1D, 2D, or 3D array/field of elements can be actuated (as with TRANSFORM, Figure 1.X and Y). Actuation can also be via air or fluid piston (pneumatics); shape-memory allow (e.g., nitinol); or of a biological process (cf. [Wang et al. 2017a]). The actuation can be viewed at a distance; or with haptic feedback. Haptic feedback variations include resistive (e.g., particle brake) and active (e.g., motor-actuated) variations.
- 2D: Actuation is commonly realized along a 2D surface (be it horizontal, vertical, or an alternate flat or curved surface). The actuating element may be held mechanically captive; or be mechanically decoupled. Latter examples include one or an array of robots (e.g., Zooids [Le Goc et al. 2016], Thumbles [Patten 2014], etc.); magnetically actuated (e.g., [Pangaro et al. 2002; Patten and Ishii 2007]); vibrationally actuated [Reznik and Canny 2001]; via microairjets [Biegelsen et al. 2000]; etc.
- 3D and higher dimensions: Actuation may also be realized with full spatial freedom (e.g., with three degrees of translational and/or rotational freedom). Examples include airborne or submersible drones; magnetically levitated artifacts [Lee et al. 2011a]; artifacts levitated using jets of air or water; etc.

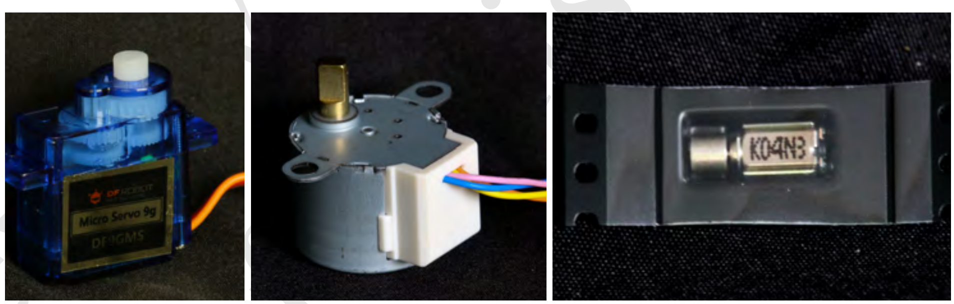


Figure 5.20 **a) Servo motor; b) Stepper motor; c) Vibration motor** [photos courtesy Brygg Ullmer].

Display and actuation technology design spectrum

In Figure 5.8, we revisited Figure 5.1 from a sensor perspective. In Figure 5.29, we do so again from a display and actuation perspective, albeit with somewhat different approach. As rationale, consider among the simplest sensors and displays: a button and an LED lamp. Regarding physical locality/proximity, it is easy to argue most mechanical buttons as "integral;" if they are not physically pushed, they do not trigger a response.

Figure 5.21 **Robotic actuation (mobile):** a) Zooids [Le Goc et al. 2016]; b) PICO (photo courtesy MIT Media Lab) [Patten and Ishii 2007]

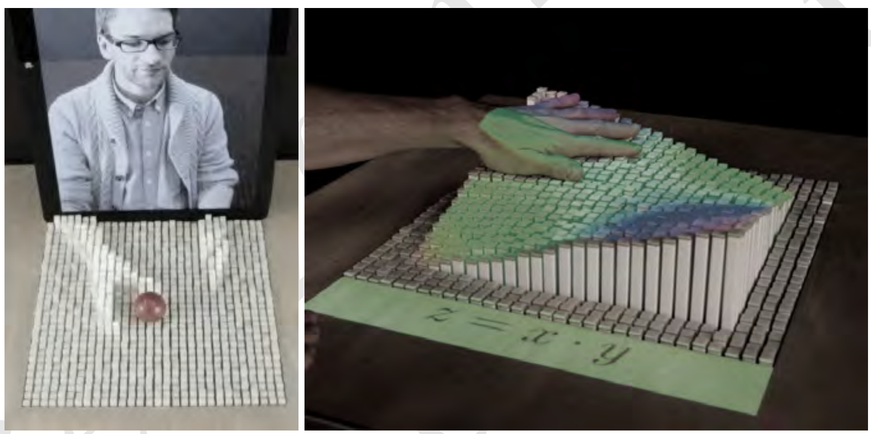


Figure 5.22 **inFORM** *(Follmer, Leithinger, Ishii, et al., MIT Media Lab, 2013): [Leithinger et al.].*

In our view, positioning LEDs regarding locality/proximity is more nuanced, and a product of use. On the one hand, if an LED or other luminous display is integrated into the surface or structure of a tangibles, and illuminates diffusely, one might characterize this as an "integral display." On the other hand, if a moderately or intensely bright LED illuminates external tangibles from a distance of centimeters, or 10s of meters, "proximal" or "distal" might be more accurate characterizations.

With this perspective, Figure 5.29 groups the display and actuation technologies surveyed in §5.6 and 5.7 into several categories, and places them per the following rationales:

- *discrete illuminators*: as we have discussed for LEDs, they, incandescent or fluorescent lamps, electroluminescent films, or other discrete illuminators can all hold integral, proximal, or distal localities relative to tangibles. Regarding "agency," we label these as "active;" when power is removed, the displayed information disappears.

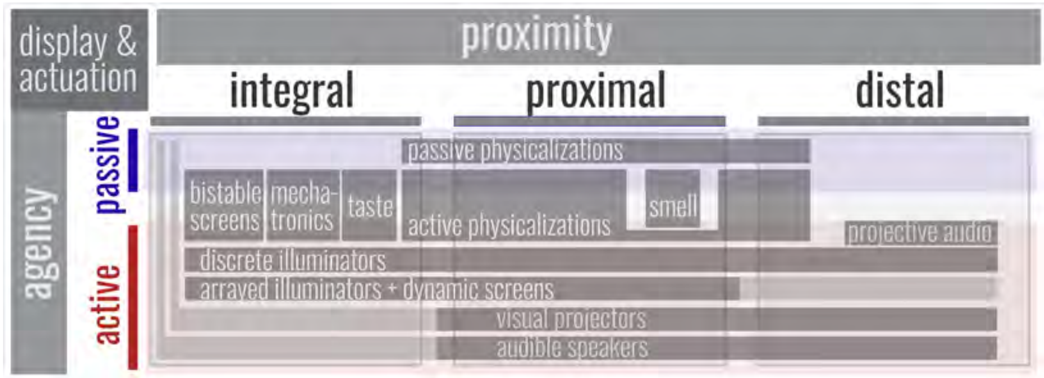


Figure 5.23 **Display and actuation technology design spectrum**

- *arrayed illuminators/screens*: Similarly, 1D, 2D, or 3D arrays of illuminators can be integral within a tangible, or proximal (e.g., toward providing “digital shadows”); and typically are active in nature. (Here, 2D arrays are most often found as screens, whether LCD, plasma, OLED, FOLED, or other.) Larger screens (whether 1m or 100+m in scale) can often be seen at a distance, and argued “distal;” we label these a lighter shade of gray.
- *visual projectors and audible speakers*: somewhat conversely to screens, both visual projectors and audible speakers are most often projected from some distance (again, be it 1m or 100m). That said, active-surface tangibles or worksurfaces are commonly realized using back-projection; and embedded-speakers, requiring ears to be pressed up against tangibles, are surely also possible. For these reasons, we label "proximal" and "distal" as most common, and integral as less common. We also somewhat extend these subspaces into passive-integral, as the physical shape of a tangible (whether passive or actuated) can sculpt its acoustics or reception of projected visuals. Projective audio (like audio spotlights, which typically originate in inaudible ultrasonic form, and become audible upon striking a physical surface) are a special case, which we note as "distal" in locality.
- *bistable screens*: where most displays and projectors revert to visual silence when power is removed, “electronic ink/paper” (e-ink) is “bistable;” the image persists. From an electrical engineering perspective, these are active devices. But from a TEI conceptual perspective, in our view, they may be most productively regarded as spanning the passive-active spectrum.
- *mechatronics*: similarly to bistable screens, many mechatronic systems (be they expressed as a single motor or solenoid, or a 1D, 2D, or 3D array of actuated elements) hold their physical state when power is removed. For this reason, we again characterize them as spanning the active/passive spectrum.

- *taste and smell*: olfactory display technologies are most often (to our understanding) somewhat persistent in nature. While (as with haptics) electrostimulation may be transitory, with olfactories realized by the expression or synthesis of chemicals, the chemicals may persist (whether for seconds or longer) even after power is removed. For this reason, they can be regarded as spanning the active/passive spectrum. Here, “integral” is a somewhat arguable label, but – we regard it as plausible to consider taste as “in” the mouth, and smell as sourced "near" the nose. While some smells are noted at a distance (e.g., forest fires), we anticipate that with the exception of performance events (e.g., concerts), distal olfactories may generally be less suited to TEI systems.
- *physicalizations*: Figure 5.29 depicts two forms of physicalizations. By current perspectives in the data physicalization community, we understand (e.g.) a 3D printed, CNC routed, or hand-crafted “physicalization” – even if untouched by continuing digital mediation – can be considered a kind of tangible. If such physicalizations are unmediated, we regard them as passive in nature. If mediated, we regard them as engaging both passive and active agency.

Computation and Communication

Tangible and embodied interfaces typically involve an intimate relationship with computation. The computational landscape is often viewed in terms of computer hardware and software. (Firmware, a form of embedded software, can also play an important role; this goes beyond our present scope.) Hundreds of books have been written on each of these, and their evolution remains highly dynamic. Here, we provide the briefest of surveys.

Hardware

Microprocessors and microcontrollers are typically the most central embedded computational hardware of tangible interfaces. Other sister computational elements include field-programmable gate arrays (FPGAs), digital signal processors (DSPs), graphic processor units (GPUs), and others. As noted, these have been used within tangible interfaces, but with less frequent use to date. They presently go beyond our scope of consideration.

Microprocessors are often regarded as more general-purpose computational elements, with microcontrollers oriented more toward embedded control of sensors and actuators. In some cases (especially in earlier decades), microprocessors and microcontrollers require some or many external components to function. Driven by miniaturization and cost reductions toward (e.g.) smartphones, entire computational systems have often been reduced to a single chip or hybrid circuit element. This has greatly reduced the cost and complexity of designing and deploying tangible interfaces.

Sometimes tangible interfaces are driven by one driving computer or embedded processor; others, by several or many. As with other mediating technologies, this computation may be integral (e.g., with embedded processors), proximal (e.g., in-room compute devices of varying nature and scale), or distal (e.g., in the cloud). As with many areas of technology, new generations of computational technology have enabled many new forms of tangible interfaces. E.g., the geometry-defining processors (GDPs) of Anagnostou and Patera were the NEC V20 (closely related to the Intel 8088, central to the IBM PC); the ToonTown and LogJam interfaces, by a modularized Motorola 6800; and many late-1990 and early-2000 tangibles, by PIC microcontrollers.

Where laptop, desktop, and server compute processors are often optimized toward maximizing bandwidth and power, embedded processing modules are often optimized for ease of integration, lower power, small size, and reduced cost. For example, where a 2017-vintage Xeon Kaby Lake processor has 1151 pins, in a form only accessible to highly automated manufacturing, many embedded compute boards require only two power pins to be connected, with one or many additional connections to sensors, actuators, etc. per suit.

At the approach of 2020, many tangible interfaces integrate hundreds of variations on the Arduino and Raspbery Pi platforms. The Arduino is a microcontroller-based ensemble of embedded processors, at several different physical and functional scales. These are often paired with sensor- and actuator-laden daughterboards (plug-on modules) called "shields," which are frequently interoperable across Arduinos by different vendors. In contrast with many alternatives of similar vintage, the Arduino was from its birth accompanied by an accessible development environment, with rich communities of practice supported by numerous open-source software libraries.

Where the Arduino has no native operating system, the Raspberry Pi family (and many other similar boards) are based upon the Linux operating system, often operating on microcontrollers originally engineered toward the implementation of smartphones. This eases the use of full-featured programming languages such as Python; kernel modifications to optimize for different applications (such as realtime audio); parallel process; etc. Like Arduino, Raspberry Pi boards come in several physical scales, with varying cost and processing power; and are often used in combination with HAT ("hardware attached on top") peripheral boards.

While the presence of the Linux operating system eases some kinds of development and debugging, it can also make such systems less suitable for timing-sensitive control. In response, it is increasingly common for one or many Linux-based boards to each control one or many Arduino or comparable control-oriented boards.

Communications

Tangibles must typically communicate with each other and/or some centralized or distributed control system. This communication can be achieved in wired or wireless fashions, via a variety of protocols (whether standardized or custom), in serial (over a single channel) or parallel (over multiple channels).

For wired communication links, common protocols include RS232; RS485 (resilient over longer distances and amidst greater electrical noise); USB; Ethernet (including power-of-

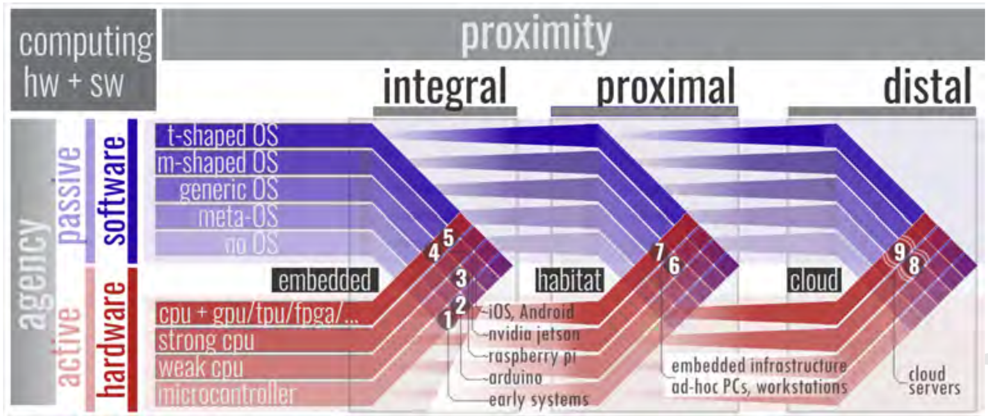


Figure 5.24 **TEI technology design space, computing perspective**

Ethernet, or POE); and OneWire protocols. A common challenge of wired communication is electromechanical noise (jitter). Especially if multiple tangibles are electromechanically coupled together, even when considerable care is taken, it is common for noise to significantly complicate and compromise system performance.

Wireless communication approaches include optical, acoustic, capacitive, magnetic, and microwave communications. Optical communications include visible and invisible (e.g., ultraviolet and infrared). Common microwave communications modalities include WiFi, Bluetooth, and Zigbee. A number of the software communications technologies referenced are within [Toole 2012].

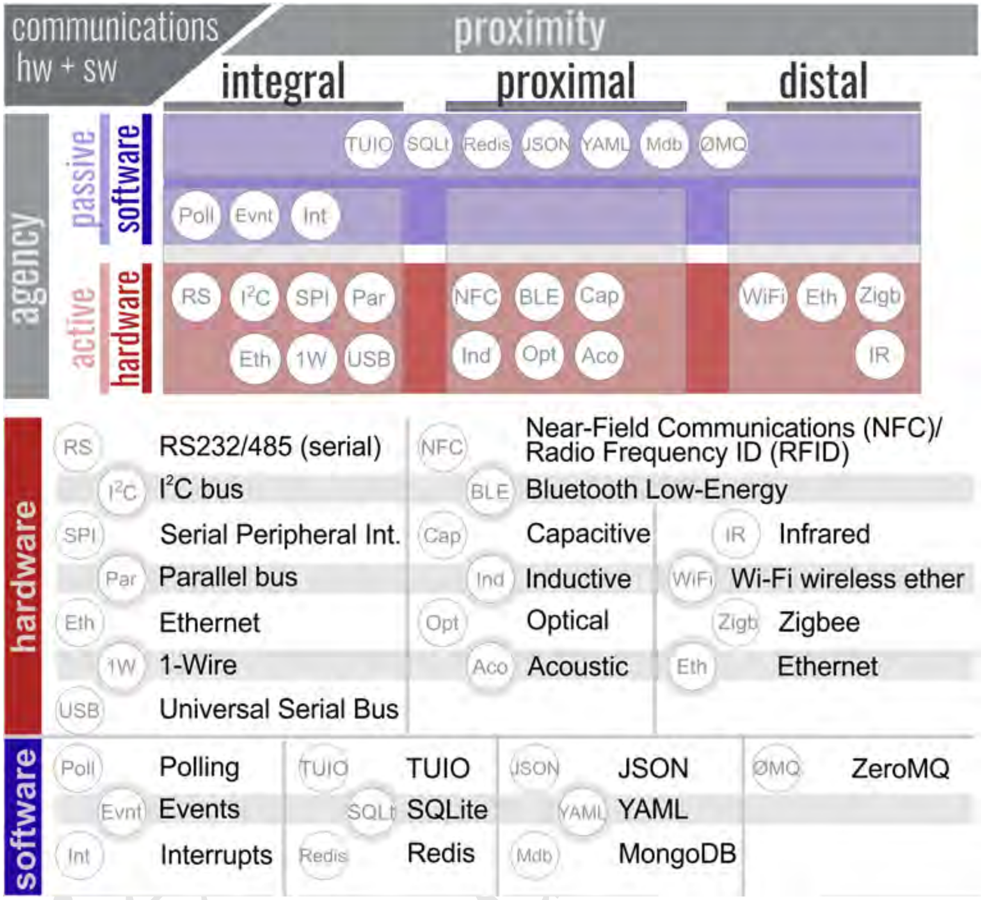


Figure 5.25 **Communication technology design spectrum**

vignette : Prof. Takeo Igarashi, U. Tokyo : Human-Computer Hybrid Fabrication

Most fabrication devices such as 3D printers and laser cutters work as non-interactive, closed systems. The user presses a button to start a fabrication process and waits until the system completes fabrication. A problem with these approaches is that the devices need to large and balky to enclose the target material and fabrication result, making it difficult to print large objects. An alternative approach is to design a fabrication device as a small open system where the human and computer work together in fabrication. Human body can easily cover larger area than desktop fabrication devices, while computer can provide detailed control.

Early examples in this approach are FreeD and Routers. FreeD is a hand held milling device. The user roughly places the tool head around the target, and the system adjust the position of the tool head to curve out a target shape from the material. Router is a hand-held sawing machine. The user roughly moves the tool along the target curve, and the system makes detailed adjustments to the position of the blade.

We applied this approach for computer-assisted drawing on a carpet. The user sweeps a roller-shaped handheld device with array of rods beneath, and the device leaves a pattern by selectively raising the carpet fibers below. Using this device, the user can draw a large monochrome image on a carpet. We also developed a pen-shaped handheld device with a rubber wheel at the tip. The rubber wheel continuously rotates to raise the fiber below. The device has embedded orientation sensor and actuator so that the orientation of the rubber wheel is always the same regardless of the user's hand movement.

We also applied this approach for architecture-scale fabrication. We first applied it to fabrication of a pavilion made of chopsticks. Human workers drop chopsticks and glue together, following guidance provided by a projector-camera system. The system measures the difference between the target shape and current configuration of the chopsticks, and then directs the human worker to put chopsticks at appropriate locations. We also build a special hand-held device for mixing and dropping chopstick-glue compound. We also applied human-computer hybrid fabrication approach to fabrication of a pavilion made of urethane form. This system works as a large-scale version of 3-draw []. Human works draw curves in the air ejecting urethane form. Urethane form immediately hardens and stay there as a solid pillar. We designed and built a dedicated hand-held tool to eject urethane form together with mesh strips to hold the form.

We believe that the human-computer hybrid fabrication is a powerful approach that is applicable to many other applications. Humans and machines have complementary strengths each other, and it is best to combine them to build efficient and effective fabrication systems. These smart tools can be seen as *active* tangible interfaces, which not only allow efficient interaction between human and computer, but also *change* the physical material as a result of interaction.

Fabrication

Physical fabrication spans far before the dawn of history. The earliest known stone tools date to (at least) 3.3 million years ago, pre-dating the earliest humans of the *Homo* genus. Fabrication also clearly is not limited to humans. Tool manufacture and use has been observed in species as diverse as elephants, many primates, dolphins, and more than thirty families of birds. The homes crafted by species as diverse as termites and beavers – and even bacteria creating their own eco-system – further illustrates the diverse heritage of fabrication. While whole books and encyclopedias have been completed for various genres of crafts and manufacturing, we only briefly survey this broad space of pursuit.

Craft and Craftsmanship

Sennett [2008] wrote the canonical book *The Craftsman* in which he explains craft as the desire to do a job well for its own sake. It is a desire for quality, building on the development of skill, driven by the motivation to do well, and based on the close connection between hand and head. To start with, the latter *"Every good craftsman conducts a dialogue between concrete practices and thinking; this dialogue evolves into sustaining habits, and these habits establish a rhythm between problem solving and problem finding."*

The keynote speaker at TEI2015, Frank Wilson, dedicated his career to hands. Wilson [1998] clearly indicated that *"the brain does not live inside the head, even though it is its formal habit. It reaches out to the body, and with the body it reaches out to the world. ... brain is hand and hand is brain."*. Sennett [2008], Wilson [1998] and Ingold [2013] stress the uniqueness of the hand, with its flexible independently moving fingers, its nails and sensitive finger pads, and its precision grip that is enabled through the rotating thumb opposite to the fingers. In this dialogue between hand and head the skill can develop, always beginning as a bodily practice. Through touching and moving and using ones hands, knowledge and skills can develop. For this process and understanding, Sennett [2008] considers imagination to be key, grounded in ambiguity and resistance which both can be considered as instructive experiences that spark imagination.

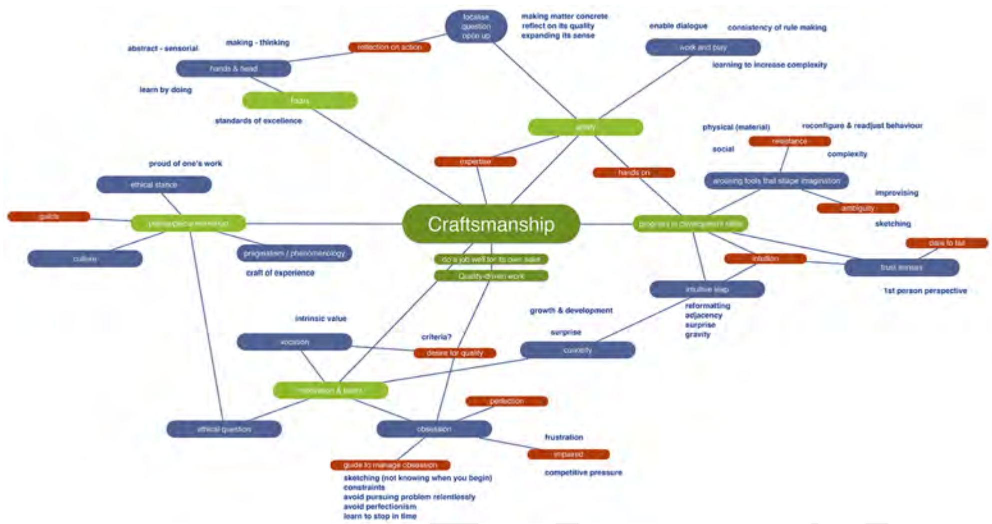


Figure 5.26 The key aspects captured and discussed in Sennett's book *The Craftsman*.

Moreover, by using imperfect or incomplete tools, the craftsman is supported to draw on his imagination in developing his skills to repair and to improvise. The third aspect Sennett [2008] considers essential for craftsmen is the focus on motivation instead of talent: *"The craftsman's desire for quality poses a motivational danger: the obsession with getting things perfectly right may deform the work itself. We are more likely to fail as craftsmen, I argue, due to our inability to organize obsession than because of our lack of ability. The Enlightenment believed that every-one possesses the ability to do good work of some kind, that there is an intelligent craftsman in most of us; that faith still makes sense."* Figure 5.26 shows our interpretation of Sennett's understanding of craftsmanship, which so clearly shows why tangible and embodied interaction is so interwoven with craftsmanship and making. It also gives us a warning. We might focus on developing tangible and embodied interactions that celebrate the hand, but if we do not utilize our hands during the making process and would move more and more to tools that do not support imagination, do not trigger our curiosity, bypass our senses and abilities of the hands, as some computer-supported tools aim to do, we will lose the strength of TEI. In a way, Sennett [2008], Wilson [1998] and Ingold [2013] remind us to practice what we preach.

Ingold [2013] shows not only the importance of the hand, the skills and the craftsman's attitude, but also the role of the material. He sees it as *the dance of agency* in which *"bodily kinaesthesia interweaves contrapuntally with the flux of materials within an encompassing morphogenetic field of forces."* So, the gesturing hands of the potter on the wet clay can be seen as a contraposition of equal forces which is also enabled by the rotation of the wheel, or as Ingold indicates, the wheel needs to correspond with the clay. And this threesome, e.g.

potter-wheel-clay, applies to all making also e.g. player – musical instrument – sound or flyer – kite – air. So, throwing a pot on a wheel or performing music is not merely interacting with the tool or instrument, it is corresponding with the clay or the sound. Ingold [2013, p102] calls these tools transducers, which *"convert the ductus – the kinetic quality of the gesture, its flow or movement – from one register, of bodily kineasthesia, to another, of material flux."* It seems that our current technology is slowly but certainly reducing the *ductus* of the entire hand and moving towards the fingertips, e.g. by focusing more on buttons and small interactive screens. The difference between graphical and embodied interaction stresses exactly the role of the *ductus* of the entire body. Traditional craft technologies, such as paper crafts, ceramics and glass crafts, textile and leather crafts, or wood, stone and metal crafts can inspire us to embrace craftsmanship and making during our own development processes, and show us ways to tap into another material quality and show us a way to approach the dance of agency. Not only with respect to the materials used, the skills of the craftsmen, but also the manufacturing processes with its transducing tools, such as forming, casting and moulding.

Personal fabrication technologies

When looking at the material study done by Hayes and Hogan [2020] we see the highest preference for the use of plastics, as well as a preference for metal, wood and paper within the TEI community. More striking, which might support the focus on craftsmanship while designing, is that almost three quarter of the materials used are one-offs. This might be explained by more practical reason, such a prize and specific technical quality, but it might also be explained the possibility of imagination through the potential of ambiguity and feeling material resistance. Since many prototypes are focusing on exploration, ideation and conceptualisation, instead of (mass) production, there seems to be many one-offs, but regarding materials as well as prototypes. With the increase of interactive technologies and tools, we also see more one-offs made not using hand-held tools but machinery, like 3D printers and laser cutters, giving rise to personal fabrication. This way of fabrication in some respects parallels personal computing and personal printing (e.g., via inexpensive laser or inkjet printers), enabling the manufacturing of artefacts using personal computing, digital data and manufacturing machines like 3D printers, laser cutters and digital looming machines. These technologies give on the one hand rise to democratization processes, enabling people to create their own artefacts at home. On the other hand, as shown above, it also forms a threat to lose the empowering quality of the "ductus" of the hand.

As with craft and manufacturing processes, personal fabrication is generally regarded as either "subtractive" or "additive." In the subtractive realm, laser cutting has come to be particularly popular. Driving factors include ease of design (e.g., with mainstream software like Adobe Illustrator and CorelDRAW); ease of fixturing (holding the materials for cutting); wide range of materials (e.g., paper, plastic, and at higher wattages, metals); and declining cost. Sister subtractive technologies such as waterjet cutting, milling, and CNC knife cutting enable thicker, alternate materials (e.g., metal, stone, and polycarbonate); or sometimes, reduced size and cost.

Among additive personal fabrication technologies, 3D printing has gained great momentum. Although existing for many decades, the dramatic decrease in cost (partly accompanying an expiration of several key patents) has greatly enhanced availability and uptake of this technology. While fabrication in plastics such as PLA, ABS, and specialty resins are most common, diverse amalgams incorporating wood, carbon or silver (for conductivity), flexible materials, translucent materials, electrically active materials, edible materials, living materials, etc. further extend the envelope of the possible. Using these personal fabrication machinery does however not per definition have to imply that the ductus and imagination is diminished, but it does require another attitude towards these machines and also the development of new skills to explore these machines in different ways. For example, Lévy and Yamada [2017]; Yamada [2016] worked on the aesthetics of the imperfection while designing artefacts for a Japanese Tea Ceremony, where they explored the notion of imperfection, inspired by the work of Yanagi [1989]. They used new production techniques like 3D-modeling and 3D-printing and left the agency of creating imperfection to the 3D-printer by changing the printing speed. This way the 3D-printer would not be able to produce "nearly perfect" artefacts, but rather create unplannable imperfection in order to obtain beautiful irregularities. It seems however that such new creative ways of using these tools have hardly entered the TEI community. Hence, we do invite you embrace the perspective of Ingold [2013] and also aiming to have dances of agency with such new transducers like 3D printers and laser cutters, where it is not about interacting with the these machines, but finding new contrapositions of equal and opposing forces enabling us to correspond in new ways with materials.

Technology Toolkits

Toolkits have long played an important role in HCI research and design, as they provide reusable abstractions that simplify the process of working with different software and hardware technologies [Myers et al. 2000]. Per Marquardt et al. [2017], toolkits can be broadly defined as *"a set of software and hardware components, programs, routines, building blocks, toolchains, concepts and interfaces that are used to prototype, design, develop, maintain and deploy interactive computing systems."*

As can be seen from the above sections, the sheer breadth of mediating technologies that are used to support sensing, display, actuation, communication and fabrication in the TEI domain has given rise to a variety of different toolkits and frameworks. While a comprehensive taxonomy of toolkits is beyond the scope of this book, we provide a brief overview of several threads of toolkit-related work that are specifically relevant for the design of TEI systems. Note that these threads are not necessarily mutually exclusive, and that some toolkits may support design and development across more than one of these areas.

Tangible Object Toolkits

Some toolkits support the creation of interactive tangible objects using sensors and actuators, often referred to as "physical computing". Other toolkits support tangible object tracking and interaction via wireless means, such as RF transmission or computer vision.

In the physical computing category, an early example is the Phidgets [Greenberg and Fitchett 2001a] toolkit, which provides a range of physical input and output components (e.g., buttons, sliders, touch sensors, motors), and makes their functionality accessible through a software-based API. Conceptually, Phidgets advanced the idea of "physical widgets" as a counterpart to GUI widgets. Other electronics prototyping toolkits include Arduino [Mellis et al. 2007] and littleBits [Bdeir 2009a]. Additionally, the LilyPad Arduino [Buechley et al. 2008a] extends from the Arduino platform and specifically targets fabric-based electronics for the design of wearables and other textile-based artifacts. Collectively, these and other related tools have helped to make physical computing broadly accessible to the interaction design community.

In the wireless object tracking category, the iStuff [Ballagas et al. 2003] and Papier-Mâché [Klemmer et al. 2004] toolkits both provide event-based models for developing applications that make use of interactive tangible objects. iStuff is built on top of the iROS [Johanson et al. 2002] interactive workspace infrastructure and consists of wireless input and output devices such as buttons, sliders, knobs, wands, lights and speakers. Papier-Mâché provides an event-based model for application development using RFID-tagged, barcoded, or computer vision identified objects.

Interactive Tabletop Toolkits

Numerous toolkits have been created to support application development for interactive tabletops that provide input through varying means, including touch, pen/stylus, and tangible objects. For example, DiamondSpin [Shen et al. 2004] was a Java-based toolkit that supported the development of multi-user multitouch tabletop applications. A core component of DiamondSpin was a polar-coordinate system that enabled flexible orientation of interface components on the tabletop display surface in order to facilitate different viewing angles for people around the table.

One of the most widely-used toolkits for tangible and multi-touch interaction on tabletop displays is the computer-vision based reacTIVision toolkit [Kaltenbrunner 2009b; Kaltenbrunner and Bencina 2007b] (see Figure 5.27). reacTIVision tracks fiducial markers and finger touches on a tabletop surface, and sends the information to client applications via the TUIO protocol [Kaltenbrunner and Echtler 2018; Kaltenbrunner et al. 2005]. An accompanying TUIO simulator application can be used to simulate tabletop events, thereby enabling developers to prototype interactive tabletop applications from their personal computers, and later deploy them to the tabletop system.

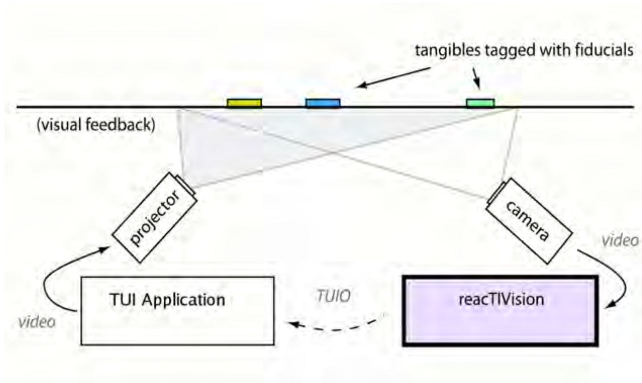


Figure 5.27 reacTIVision [Kaltenbrunner and Bencina 2007b] is a computer-vision based framework that tracks fiducial markers and finger touches on a tabletop surface and sends the information to client applications via the TUIO protocol.

Cross-Device Interaction Toolkits

Over the past decade, there has been a growing interest in cross-device interaction toolkits to support the development of applications that span multiple (typically screen-based) devices, such as smartphones, tablets, interactives tables and interactive walls. Brudy et al. [2019] provide a comprehensive survey of this space, noting that there has been little consistency in the terminology used to describe the different kinds of toolkits that have been created and the types of interactive computing systems they support. Notably, they provide a taxonomy of key characteristics to scope and frame the cross-device interaction design space. The six dimensions they use to define cross-device systems are: 1) *Temporal* – are the interactions synchronous or asynchronous? 2) *Configuration* – is the system setup mirrored, distributed, migratory or cross-platform? 3) *Relationship* – what are the people-to-device relationships? 4) *Scale* – is the physical scale of the system near, personal, social, or public? 5) *Dynamics* – is the system setup ad hoc/mobile, semi-fixed or fixed? 6) *Space* – are the interactions co-located or remote.

Particularly relevant to the TEI domain are cross-device interaction toolkits that support not only screen-based devices, but also tangible and/or embodied interactions. An early example is iROS, an event-based software infrastructure that was designed to support the iRoom interactive workspace environment [Johanson et al. 2002]. iROS supported the various iRoom components, such as touch-sensitive whiteboard displays, an interactive wall and table, wireless buttons, and an overhead scanner that could be used to digitize sketches and other physical materials placed on a tabletop. Other example toolkits that address different aspects of the cross-device/TEI design space include Shared Substance [Gjerlufsen et al. 2011], the Responsive Objects, Surfaces and Spaces (ROSS) API [Wu et al. 2012], the Society of Devices (SoD)

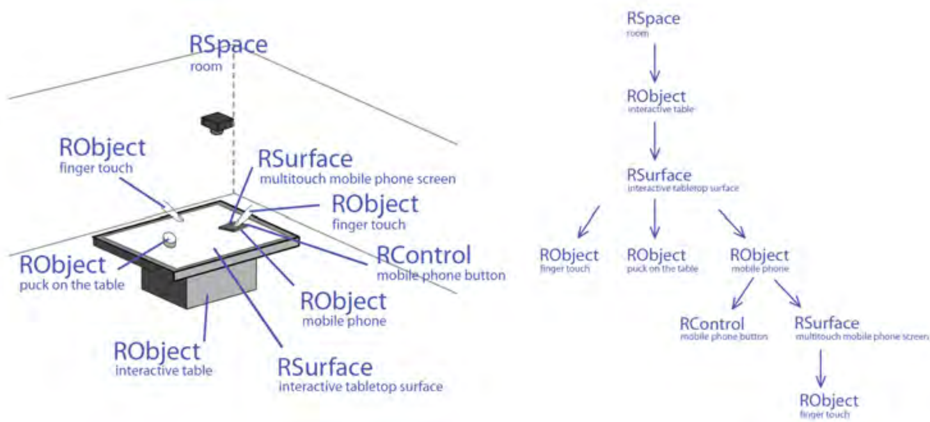


Figure 5.28 The Responsive Objects, Surfaces and Spaces (ROSS) API [Wu et al. 2012] is a toolkit to support application development in the TEI/cross-device design space. ROSS is based on the idea that interactive spaces, surfaces and objects exist in nested relationships with respect to one another, as shown here for an interactive space that contains an interactive table with a number of tracked objects on its surface.

Toolkit [Seyed et al. 2015], and the Entities, Components, Couplings and Ecosystems (ECCE) Toolkit [Bellucci et al. 2017]. Shared Substance [Gjerlufsen et al. 2011] addresses not only heterogeneous devices, ranging from small and large surface-based devices to spatially tracked custom tangibles, but also heterogeneous content from different sources, along with associated display methods. The ROSS API [Wu et al. 2012] (see Figure 5.28) is based on the core idea that interactive spaces, surfaces, and objects exist in nested relationships with respect to one another. As such, the API provides a common abstraction (in the form of an XML descriptor) that developers can use to define their target environment based on these relationships. The SoD Toolkit [Seyed et al. 2015] addresses a range of standard devices, such as smart watches, mobile devices, interactive tables and walls, and head-mounted displays, as well as full-body and gestural interactions based on the Microsoft Kinect and LeapMotion sensors. Lastly, the ECCE Toolkit [Bellucci et al. 2017] spans not only off-the-shelf devices such as smartphones and tablets, but also provides tools that support the end user in circuit design and the physical assembly of objects with embedded electronics.

Fabrication Toolkits

As described in section 5.9, the area of TEI design has grown in parallel to the rise of personal fabrication and “maker” culture, with the emergence of reasonably-priced consumer-level rapid prototyping technologies such as 3D printers and lasercutters playing a central role in this space. However, TEI designers are not necessarily experts in physical design and fabrication, and as a result there is an opportunity and a need to develop toolkits that can support this aspect of TEI design.

Baudisch and Mueller [2016] provide a comprehensive review of the personal fabrication space, highlighting the required elements for making fabrication processes accessible to consumers and other non-experts. At the HCI and toolkit-related level, these key elements include the ability of the software tool to: 1) facilitate expert tasks by embodying domain knowledge that non-experts lack, 2) facilitate trial-and-error exploration by providing feedback through interactivity, and 3) facilitate the workflow by encapsulating the necessary knowledge about the machine. We provide a few examples of fabrication-related toolkits that are relevant to TEI design.

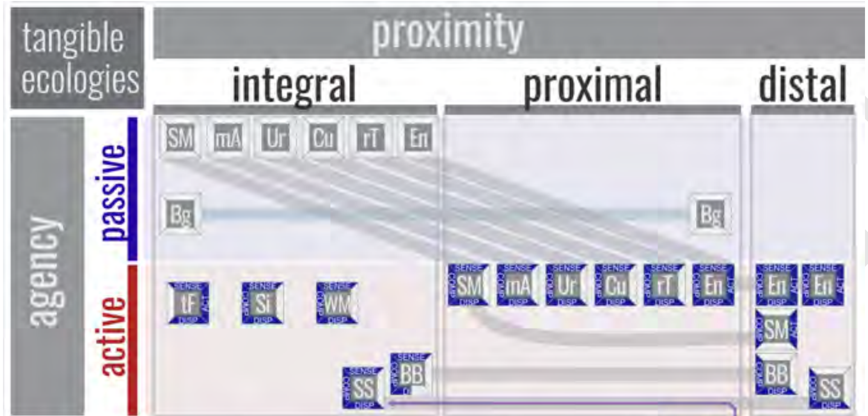
Web companion 5.8 (tech/figs/a8)

FormFab [Mueller et al. 2019] is an interactive fabrication tool in which users control the sculpting of thermoplastic material in real-time using hand gestures to (a) keep the plastic at its current level, or to (b) increase pressure or (c) decrease pressure / switch to vacuum, in order to shape the plastic outward or inward, respectively.

Some fabrication toolkits are designed for a very specific and narrow set of design tasks, such as the SketchChair [Saul et al. 2010] tool for designing and building chairs, and the Pteromys [Umetani et al. 2014] tool for creating custom gliders. Other toolkits tackle a somewhat broader space, such as the Enclosed [Weichel et al. 2013] tool for generating enclosures for electronic prototypes, and the RetroFab [Ramakers et al. 2016] design and fabrication tool for retrofitting various legacy devices such as old household appliances to allow for automation, remote control, and interconnection.

The "interactive fabrication" space mapped out by Willis et al. [2010] offers another approach to supporting physical fabrication. In interactive fabrication, users are provided with the controls to operate digital fabrication devices in real time, thereby bringing the creative design and construction parts of the process closer together. For example, CopyCAD [Follmer et al. 2010] uses a camera and projector system to allow users to sketch directly onto a physical object, and then have these sketches cut directly into the object with a 3-axis milling machine. Other examples of interactive fabrication include Constructable [Mueller et al. 2012], in which users draw the paths to be lasercut directly onto the workpiece using a laser pointer, and FormFab [Mueller et al. 2019] (see Figure 5.10.4), in which users direct the sculpting of thermoplastic material in real-time using hand gestures.

As these examples show, research on fabrication toolkits has tackled different parts of the design and fabrication process, addressing some of the challenges that non-experts face in making physical things. While much of this work has been in a prototype form, these efforts are paving the way for new kinds of tools and abstractions that will further facilitate TEI design going forward.



Illustrative systems	~Tokens	~Constraints	Complements
Slot Machine	Cards	Slots	Robot
Building Block Systems	Blocks		Screen
Marble Answering mach	Marbles	Machine	
Urp	Models	Table	
Cubby	Tools	Workspace	
Enodia	Hextoks	Worksurf	Oculus Runway
Board games	Pieces	Board	
TRANSFORM		Workspace	
Sifteo	Cubes		
Wearable Motherboard		Vest	
SMS Slingshot	Slingshot		Buildings

Figure 5.29 Engagements of different mediating technologies with illustrative TEI systems of Chapter 1

Summary

In concluding remarks, prototyping is a critical part of fabrication that we have thus far left unmentioned. Beaudouin-Lafon and Mackay's text on the topic is particularly commended [Beaudouin-Lafon and Mackay 2009]. Also, partly per the "contrast" principle which we will discuss in the beginning of the next chapter, hybrid approaches – e.g., fabrication using multiple complementary processes and materials – often allow aesthetic and functional processes extending beyond the possibility of any individual medium.

6 Aesthetics of TEI

In the chapters up till now, we provided an overview of tangible and embodied interaction in the lab and the wild, as well as a deeper investigation with respect to frameworks, cognitive and philosophical dimensions next to technological characteristics and opportunities. This chapter focuses on designing tangible and embodied interaction. How to create meaningful interactions, and how to ride the notion of tangibility and embodiment (or should we say animacy after Ingold [2013] instead of interaction?), and how to play with the richness and subtleties of materials and dynamics to fit the skills and modalities of a person?

Introducing Aesthetics of Interaction

Technology mediates between humans and their environment and co-shapes our being-in-the-world, including our actions, perception, experiences, and our understanding of the world [Ihde 1995; Rosenberger and Verbeek 2015a]. According to Merleau-Ponty [1962], the body opens up to our environment in different ways. Hummels [2012] explains these different ways with the example of a skateboarder trying to jump a ridge: *"Firstly, the world opens up through the actual shape and innate capacities of the human body; the ridge is jumpable because the skateboarder has legs that can bend and stretch to generate the power to jump, and he has two feet that give him stability on the skateboard. Secondly, we have skills for coping with the world, and as we refine these skills, e.g. by practising jumping with the skateboard, things show up as soliciting our skilful responses, so that as we refine our skills, we encounter more and more differentiated solicitations to act. Thus, while improving his skills of jumping, the skateboarder perceives his environment differently and sees more and more possibilities for jumping. Thirdly, the cultural world has a relationship with our body. Only because we Western Europeans are brought up with skateboards in concrete cities where it is OK to jump on benches, specific ridges solicit the skateboarder to jump on them [Dreyfus 1996]. So, meaning is created in interaction by the skateboarder who is trying to get a maximum grip on that specific situation."*. But not all cities are fond of this behaviour, and we can spot many instances of 'hostile design' in public space, which aim to prevent specific behaviour and even specific people in public areas, such as preventing skaters making use of parks ans squares, and jumping all kind of public furniture [Rosenberger 2018, 2020].

As the example shows, technologies like skateboards and public furniture are not neutral, but a medium between humans (with specific skills, experiences and a specific socio-cultural history) and the world (with its specific socio-cultural, technological, economic, political, religious, spiritual, ... dimensions). Humans, technology and the world are an inseparable unity, constituting each other in interaction. This implies that when designing new technology, we have to explore and question how to support the creation of meaning in interaction. Or as Dourish [2001c] is saying *"the design concern is not simply what kinds of physical skills, say, we might be able to capitalize upon in a tangible interface, or what sorts of contextual factors we can detect and encode into a ubiquitous computing model. Instead, we need to be able to consider how those skills or factors contribute to the meaningfulness of actions."*

This brings us automatically to the questions, what is meaningfulness and how to design for it? In order not to drown in a deep philosophical debate, we take a rather down to earth approach in this chapter, where we approach the creation of meaning from an aesthetics point of view.

Semantic versus Embodied Approach

When looking at aesthetics, we see two main approaches to create meaning in tangible and embodied interaction: the semantic approach and the direct approach [Djajadiningrat et al. 2002a; Fishkin 2004], although in practice they can be intermingled.

The semantic approach is based on cognition and semantics, using symbols and signs to communicate information [Aldersley-Williams et al. 1990; Krippendorff and Butter 1984], often by means of metaphors referring to the shapes, motions or manipulations of other objects, animals or people. The semantic approach is about the knowable [Djajadiningrat et al. 2002a]. Metaphors in design [Casakin 2007] and design for emotions [Demirbilek and Sener 2003] can be considered semantic. Examples within the field of TEI are, e.g., TOBE (Tangible Out-of-Body Experiences) (see Figure 6.1 top left), a small tangible avatar that visualises a person's inner state based on physiological signals such as heart rate or brain activity [Gervais et al. 2016]. The presentation tool of Hemmert and Joost [2016] uses embodied metaphors for interactions with mnemonic objects in live presentations, thus placing a metaphorical approach into an embodied setting (see Figure 6.1 top right and bottom).

Even though a device is incorporating or leaning on semantics, when looking at tangible and embodied interaction there is generally a physical part which calls upon a person's perceptual-motor skills, hence it will always partly rely on the second approach: the direct or embodied approach. This approach is based on our action possibilities, and the notion that our skillful body is solicited by the situation trying to find maximum grip on the situation [Dreyfus 1996; Merleau-Ponty 1962]. Interaction is based upon affordances in relation to our effectivities, i.e., what we can perceive and what we can do with our body in a specific situation [Gibson 1979b]. The direct or embodied approach is about the tangible [Djajadiningrat et al. 2002a]. Somaesthetics [Höök 2018b; Shusterman 2012] and pragmatic aesthetics [Petersen et al. 2004] are approaches based on embodiment and the direct approach. For example, Rasmussen et al. [2016] developed Reflex, a shape-changing phone which is developed to enhance our perceptual-motor skills, even though it still has links to semantics, e.g., when the phone is pulsating up and down to attract attention and indicate that there is an upcoming meeting

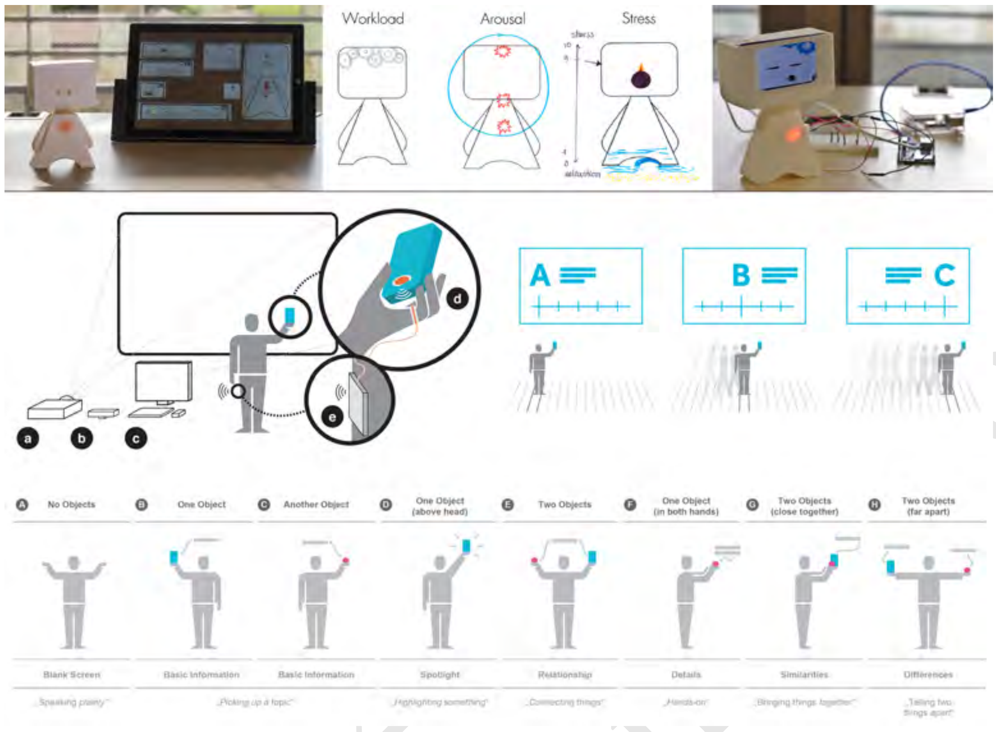


Figure 6.1 Semantics in TEI, (top) TOBE is an avatar to express a person's inner state [Gervais et al. 2016]; (bottom) embodied metaphors are used to control the slides in live presentations [Hemmert and Joost 2016]

(see Figure 6.2 on the left). The Augmented Speed-skate Experience (ASE) is developed by Stienstra [2016; 2011] to enable professional speed skaters to reflect on and improve their technique. The data gathered by sensors in the skate (green block in the middle photo of Figure 6.2) are translated into auditory feedback, more specifically into continuously changing white noise. The amount of pressure towards the ice is translated into the loudness of the noise, whereby the left speed skate is connected to the left ear and the right speed skate to the right ear. Moreover, the pitch of the noise changes while leaning more on the front (high pitch) or back of a speed skate (low pitch). Over time, every skater individually creates meaning of this sonification in action (see Figure 6.2: middle and right).

Hummels and Ross explored the characteristics of these different relationships through the interaction research installation ISH (see Figure 6.3 top), and well as the installation Coppia Espressiva (see Figure 6.3 bottom) to see which type of relation resonates with which person in which situation [Hummels et al. 2003]. ISH explored if people have a preference for a certain type of relationship, if they resonate with a specific form of interaction and if so why. The

Figure 6.2 The direct or embodied approach towards TEI, e.g. Reflex, a shape-changing phone [Rasmussen et al. 2016], and Augmented Speed-skate Experience, a sonification device to enhance speed skating skills [Stienstra 2016; Stienstra et al. 2011]

installation consists of dozens of artefacts and by playing together, people can create an image- and soundscape. Coppia Espressiva tested the difference between using a semantic approach versus a direct or embodied approach. Poco, based on a semantic approach, offers three sets of phycons to create music: one set representing various kinds of rhythms, one set representing various kinds of two-chord progressions, and one set representing various kinds of sampled sounds of nature (rain, birds etc.). Moto, developed to support a direct approach, consists of a water reservoir and by moving one or two tools through it, a person can create a musical expression.

Not to a surprise, resonance is an individual experience and highly dependent upon the person and the situation at hand. Nevertheless, we did see that control and experiencing the relation between cause and effect increases resonance. This does not mean that there has to be unity of location, direction, modality and time with respect to the user's actions and the product's feedback. However, a natural mapping between product appearance, interaction and resulting feedback is important. Moreover, intimacy and engagement during interaction are generally considered essential to increase resonance.

Aesthetics of Interaction in Interactive Products and Systems

Resonant interaction can be considered to be a form of aesthetic interaction, where the aesthetics emerge from the dynamic interplay between a person and an artefact in a specific context [Hummels 2000a]. However, resonance is not the only label used for this dynamically arising beauty.

Gillian Crampton Smith explains Tony Dunne's concept of "aesthetics of use" being *"an aesthetics which, through the interactivity made possible by computing, seeks a developing and more nuanced cooperation with the object - a cooperation which, it is hoped, might enhance social contact and everyday experience. Such an aesthetics, clearly, attends less to how an object looks, the traditional concern of product aesthetics, than to how it behaves"* [Crampton Smith].

Figure 6.3 The installation ISH (top) enables the creation of image and soundscapes (Reprinted by permission from Springer Nature: Springer, Personal and Ubiquitous Computing, Move to get moved: a search for methods, tools and knowledge to design for expressive and rich movement-based interaction, Hummels C., Overbeeke, K. and Klooster, S. Copyright © 2006, Springer-Verlag London Limited) Coppia Espressiva (middle and bottom) tests the difference between using a semantic approach versus a direct or embodied approach. Poco uses phycons to create music (bottom left) and Moto (bottom right) uses tools to directly manipulate music through movement [Hummels et al. 2003]

There is a wide variety of literature addressing aesthetics, of which the majority, as Dunne also indicates, focuses on the aesthetics of appearance. For the field of tangible and embodied interaction, the aesthetics of use [Dunne 1999], the aesthetics of interaction [Overbeeke et al. 2003b], pragmatic aesthetics [Petersen et al. 2004], etc. are crucial, since they are focusing on the aesthetics of interactivity and dynamics. Shusterman [1995] proposes pragmatic aesthetics as opposed to analytical aesthetics, which was coined by Moore [1903] and which suggests that aesthetics are solely a property of the object as if it exists in isolation. Similar to the foundations of embodied interaction, Shusterman stresses the importance of the social-cultural setting, i.e. our being-in-the-world, while building upon Dewey's work [Dewey 1987]. So, aesthetics is not an inherent property of the artefact itself, but it is a result of the human appropriation and use of the artefact. Or as said above, meaning is created in interaction. Petersen et al. [2004] elucidate this by saying that *"the chair is not aesthetic in itself but rather the aesthetic chair is a result of the socio-historical appreciation of the material, and the shapes. Accordingly our ability to engage in an aesthetic experience is based on our social context, manifested in a personal bodily and intellectual experience prolonged beyond the immediate experience. According to the thinking in pragmatist aesthetics, aesthetic is not something a priori in the world, but a potential that is released in dialogue as we experience the world; it is based on valuable use relations influencing the construction of our everyday life."*

In general, aesthetics of interaction can be considered to be a sense of beauty which arises during the dynamic interplay between a user and an artefact in their context [Hummels 2000a]. The aesthetics of interaction or pragmatic aesthetics refers to affect that arises during interaction, and according to Locher et al. [2010] it is closely related to Csìkszentmihályi and Robinson's flow experience [Csìkszentmihályi and Robinson 1990], which states that individuals engage art objects *"not because they expect a result or reward after the activity is concluded, but because they enjoy what they are doing to the extent that experiencing the activity becomes its own reward."* The deep involvement in interacting with the artwork is the main goal. Locher et al. [2010] consider that this deep involvement when experiencing art is the same type of involvement during an aesthetic experience with interactive products and systems. This aesthetic experience is not merely linked to a bodily experience nor only a cognitive experience, but the aesthetic experience speaks to both the mind and the body. According to Petersen et al. [2004], this implies that when developing tangible and embodied interaction, we should not merely focus on gratifying our bodily perceptual-motor skills, but also challenge and please our intellectual capacity by sparking our imagination and enabling people to make sense of complex, contradictory and even ambiguous systems and situations, as Gaver et al. [2003] called for in his publication.

The question then remains to explore and discuss what creates this affect and sense of beauty. Why are some devices considered beautiful and meaningful by some people and not by others, or in some situations and not in others? We consider three dimensions to be important when trying to evoke pragmatic aesthetics when being engaged in tangible and embodied interaction:

- Tangible and embodied interaction in a socio-cultural context, especially the interaction possibilities, invitation and appropriation.
- The person's abilities, values, skills and needs while interacting.
- The richness of the artefact including their form, materials and dynamics qualities to realise aesthetics in interaction.

In the remaining part of this chapter, we will discuss these three dimensions related to the aesthetics of tangible and embodied interaction to support developers during their design process. Firstly, we will elucidate various ways in which TEI-oriented designs can enable and anticipate possibilities for interaction and experience, and how they can be appropriated and used by people. Thereupon, we describe the design dimensions when starting from the person and his body: the values, skills, multi-modalities, concepts of the body and spectrum of movements. In the third section, we focus on the design dimensions of the tangible and embodied device itself to realise aesthetics in interaction: its material and dynamic qualities. We conclude this chapter with different design processes and principles that can support the quest for the aesthetics of interaction.

Variety of Possibilities, Invitations and Appropriation of TEI

Tangible and embodied interactions can come in many different ways and have many different forms and opportunities. TEI technology mediates our relations with the world in various ways. Ihde [1995] and Rosenberger and Verbeek [2015a] discerns five of such relations: embodied, hermeneutic, alterity, background and cyborg relations. With embodied relations, Idhe refers to technology that transforms a human's actional and perceptual engagement with the world, e.g. a pair of glasses enables us to see the world sharper. Hermeneutic relations refer to technology which requires our interpretation, e.g. when a thermostat shows 20°C / 68°F in a room, we have learned to understand what this number means. Alterity relations occur when humans interact with a technology as a quasi-other, e.g. we are having a kind of 'dialogue' with the interface of the ATM machine when making a cash withdrawal.

Ihde [1995] indicates a fourth, more passive background relation, which is not directly noticeable and only appears when a situation drastically changes, is broken or when putting specific attention towards it, e.g. when suddenly hearing the sound of the fridge when the room becomes uncomfortably quiet. Lastly, Rosenberger and Verbeek [2015a] add cyborg relations to the four previous ones, referring to technologies that merge with our physical body, so-called fusion relations, such as a pacemaker, or to technologies that merge with our environment, so-called immersion relations, such as an intelligent lighting system that automatically turns on and adjusts the lighting condition when being in the room.

In the first two chapters of this book, we already saw a large variety of designs which can be mapped according to these five relations. However, from a design perspective, this categorisation of relations is rather coarse, and one needs to address more detailed and nuanced aspects during the design process. Most of the time a combination of various relationships is used instead of one single relation. For example, if we look at the Reactable from Jordà et al. [2007b] as also discussed in chapter 1, we see that when a person turns the dials, the objects feel as an extension of the hand when turning (embodied relation), while the icons and graphical feedback surrounding them have to be interpreted in order to understand what they mean (hermeneutic relation). Moreover, the beamer and tracking technology underneath the table is generally not noticed during interaction (background relation).

Next to this, the five relations proposed by Idhe, Rosenberg and Verbeek seem to refer mostly to perceptual-motor skills and cognition, whereas emotional and social-cultural aspects seem less explicit in their model. Although we see Idhe' and Verbeek's types of relations as very useful, they are not all encompassing for the purpose of designing tangible and embodied interaction. Hence, in this chapter, we've used the combination of these five relations as a starting point to scan TEI-related publications in journals and conference proceedings over the years, and we complemented these 5 relations with others where needed. This has resulted in the following classification of designs and interactions that focus on mediating relations with a different scope regarding possibilities, invitation and appropriation (see Figure 6.4):

1. Sensing and extending the body
   - Sensing the body
   - On and in body extension of our perceptual-motor skills
2. Accessing the world
   - Accessing the world through our perceptual-motor skills
   - Hermeneutics for accessing (un)graspable matter
3. Specific forms of interaction with the world
   - Shape changing interfaces and programmable materials
   - Poetical, magical and extraordinary interaction
   - Peripheral perception and interaction
4. Empowering and expressing ourselves in our socio-cultural context
   - Empowering ourselves in our socio-cultural context
   - Expressing ourselves and connected socio-cultural realms
5. Social interaction
   - Interacting and collaborating with people and beyond

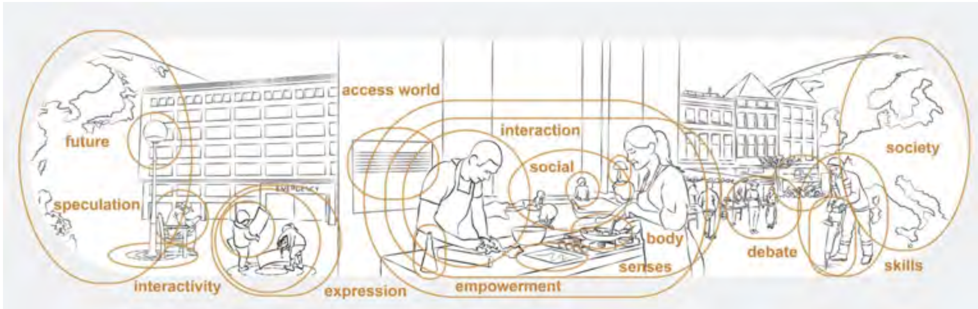


Figure 6.4 Classification of designs and interactions with various potential purposes and mediating relations (picture by Caroline Hummels).

6. Socio-cultural debate and speculation
    - Addressing socio-cultural issues via art and debate
    - Speculative design, critical design and design fiction

This classification starts with a personal relation between an object and a user, and slowly extends the relation from the person to the world and other people around, towards complex multi-persons / multi-spaces interactions.

We do not pretend to have created a complete overview nor an overview without overlapping categories. The aim of this classification is showing the broad scope of possibilities, and supporting developers to examine and question their own intentions with their designs. Mind you, this doesn't imply that people using the designs will automatically appropriate or use them in a similar way as was intended by its maker. Ihde [1995] indicates that technologies are multi-stable, meaning that they can have different interpretations, intentions and identities. Hence, technology might mean something different and afford different interactions for its users than intended by the creator. Moreover, in this overview, we might also have stressed our interpretation of the design, which might conceal a different connotation of the device as intended by its maker.

Category 1: Sensing and Extending the Body

We discern in this category two direct relationships with our body, one where technology helps us to sense our body, and another where we use technology as an on or in body extension of our person's perceptual-motor skills. Both will be elucidated in this section (see Figure 6.5).

Sensing the Body

Tangible and embodied interaction starts from the body, capitalising on our physical skills and supporting our lived experience. One of the basic possibilities of embodied interaction

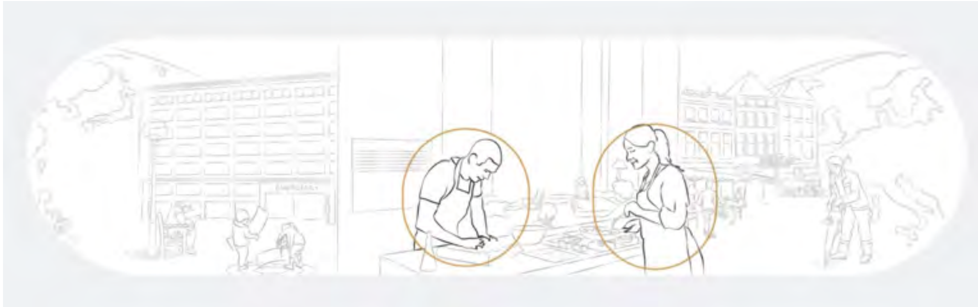


Figure 6.5 Category 1: Sensing and extending the body (picture by Caroline Hummels).

is connecting us with our own body, enabling us to sense our body and increase awareness, which is also studied by somatics: *"Somatics is the field which studies the 'soma': namely the body as perceived from within by first-person perception. When a human being is observed from the outside—i.e., from a third-person viewpoint—the phenomena of a human 'body' is perceived. But, when the same human being is observed from the first-person viewpoint of his own proprioceptive senses, a categorically different phenomenon is perceived: the human soma"* [Hannah 1995].

Closely related to somatics is somaesthetics, which was coined by Shusterman [2012] and brought to the TEI community by Kristina Höök [2018b]. With Soma Mat and Breathing Light (see Figure 6.6 top left), Höök, Ståhl and their colleagues [Ståhl et al. 2016] offered heath and ambient lighting to guide a person paying attention to his or her different body parts while simultaneously making slow movements. Another form of kinaesthetically sensing one's own body is done by Svanaes and Solheim [2016] through their mechanical tail and ears (see Figure 6.6 middle left). The tail allows its wearers to reconnect to their tailbone and obtain a very old form of expression known in nature, waiving one's tail, thus getting a completely different sensation of one's own body. Or as Dag states, the tail *"becomes a natural part of the living body and thus can take advantage of the user's 'bodily-kinesthetic intelligence"'* [Svanaes and Solheim 2016]. A related wearable is Snap-Snap T-Shirt developed by Mironcika et al. [2020], which stimulates posture awareness of a person through a playful and somaesthetic experience (see Figure 6.6 top right). By moving the body, the garment gives a different sensorial awareness with use of magnets, thus providing rich haptic feedback for posture awareness in the context of repetitive strain injury.

Next to getting kinaesthetic feedback to get in touch with one's own body, there can also be other forms of feedback, as Breathing Light already exemplified. With his interactive artwork BrightHearts, Khut [2016] offers biofeedback to children undergoing painful medical treatment in order to reduce their pain and anxiety. Their heart rate is connected to the aesthetics of the overlapping concentric circles on the graphical interface of a smartphone (see Figure

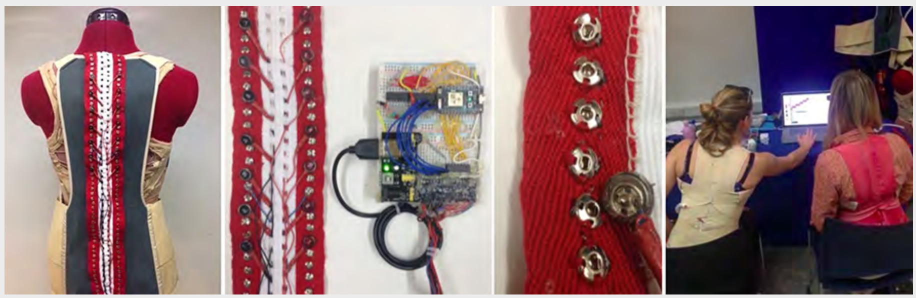
Figure 6.6 Soma Mat and Breathing Light (top left) [Ståhl et al. 2016], Snap-Snap T-Shirt (top right) [Mironcika et al. 2020], mechanical tail (middle left) [Svanaes and Solheim 2016], BrightHearts, iOS application (middle right) [Khut 2016] and POEME (bottom) [Cuykendall et al. 2016].

6.6 middle right). The more relaxed a child is, the less bright the colours are, while new layers of circles appear and gentle chimes are heard. Cuykendall et al. [2016] developed POEME, a mobile website that uses poetry as a feedback mechanism to express a person's kinaesthetic experiences and the overall understanding of his/her movements (see Figure 6.6 bottom).

Diego Maranan, Associate Professor University of the Philippines Open University
How the floor can facilitate self-sensing and inspire somaesthetic technology design

Technologies can enhance our ability to sense (and make sense of) our physical selves. Even deceptively basic artifacts can facilitate self-sensing, and examining how they do so can lead to some interesting insights on designing for embodied interaction. For instance, a smooth, flat, horizontal surface—such as an ordinary wooden floor—is an essential aid to developing somatic knowledge in the Feldenkrais Method [Feldenkrais 1972], an educational approach to sensorimotor learning that had contributed significantly to Shusterman's development of somaesthetics. The modern hard floor is a peculiar human invention. With the exception of, say, a frozen lake, few surfaces in nature are perfectly smooth, uniformly flat, absolutely horizontal, and capable of supporting the weight of the human body. Such surfaces can generate sensations that are particularly amenable to systematic observation and, consequently, enhanced body awareness. In contrast, natural surfaces are often riddled with noisy features that complicate prediction and interpretation of sensations that are felt when interacting with such surfaces. In the epistemology of the Feldenkrais Method, you can observe your neuromuscular response to gravity through attending to your body's contact with the floor. This neuromuscular organization can be altered after doing and carefully attending to the slow, gentle movements typical of a Feldenkrais Method lesson. You can glean additional insight about your neuromuscular organization by noting any differences in how your left and right sides contact the floor, using a kind of comparative analysis of embodied phenomena wherein the floor acts like a *kinaesthetic mirror* [Wildman 2008, p.64]. If the surface on which you're resting is not smooth, flat, and horizontal, any differences you sense may not provide you accurate information about your neuromuscular organization. In other words, when coupled with attentive observation, the *physical properties of the floor provide a uniform learning environment that affords proprioceptive distinction-making*.

The wearable device my co-authors and I presented at the Works-in-Progress session at TEI 2020—called *Haplós* [Maranan 2017; Maranan et al. 2020] was inspired by simple artifacts that afford sensory attentiveness, such as the modern hard floor as described here. It additionally built on the work of designers and artists from the field of embodied interaction technology research [Höök et al. 2015; Loke et al. 2013; Schiphorst 2008] and somatic costuming [Dean 2015]. Finally, *Haplós*s was motivated by research in neuroscience suggesting that vibrotactile stimulation can alter the cortical representation of the body [Rosenkranz and Rothwell 2004]. Through carefully designed patterns of vibrotactile stimulation, *Haplós* aims to elicit self-reports of heightened body awareness by supplying the user with higher-resolution information of body areas in order to increase their representation in the somatosensory cortex. As such, *Haplós* could be regarded as an example of a somaesthetic technology [Maranan 2017] in that it enhances the ability of its wearer to make systematic observations of pleasurable, structured stimuli that lead to heightened awareness. Thus, *Haplós* encourages its user to treat the body as the site both *for aesthesis (sensory appreciation) and creative self-fashioning* [Shusterman 2008, p.1].



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On and In Body Extensions of Our Perceptual-Motor Skills

Next to enhancing the sensorial awareness of one's own body, tangible and embodied interaction also allows for direct enhancement of a person's perceptual-motor skills. Dag's tail is already an example that not only enables the wearer to sense his or her body differently, but also extends the person's perceptual and motor skills. The wearer senses the environment differently through the tail which becomes a bodily extension of the person wearing it. Dag even indicated that he is feeling hampered or missing part of his body, when he doesn't wear it [Svanaes and Solheim 2016]. In this section, we discern devices which are developed to become an inseparable part of the human body like Dag's tail or a pair of glasses, offering new possibilities and improving or enhancing perceptual-motor skills. Such devices are also developed for challenged people extending or even replacing parts of their body. For example, Music-touch Shoes were developed to support hearing handicapped dancers to feel the rhythm and tempo of music through the vibrotactile interaction in their dancing shoes [Yao et al. 2010] (see Figure 6.7 top left). Technology can also support persons doing tasks which are challenging for their bodies and causing fatigue, by enhancing muscle power such as the wearable soft robotic orthosis developed to support people's corpus during work (see Figure 6.7 top right) [Flechtner et al. 2020].

Web companion 6.1 (design/figs/a1)

Stelarc speaking on Third Hand project [Photo by Matias Garabedian from Montreal, Canada - Stelarc conference Montréal, cropped, CC BY-SA 2.0 [a]];

[a] https://commons.wikimedia.org/w/index.php?curid=40526350

Next to this, we also see designs that extend the normal working of our body, but in an enhanced way. For example, we transpire / sweat which increases with intensified physical activity. BioLogic Second Skin developed by the Tangible Media Group at MIT [Yao et al. 2015a, 2016] opens little triangles to improve cooling of the body of dancers and gives on top of this a beautiful poetic expression to the dance, showing that a tangible and embodied design can have multiple purposes and mediating relations (see Figure 6.7 middle). Tangibles can also explore new perspectives regarding our skills and perception of our skills. For example, Danielle Wilde [Wilde 2010] developed a variety of body-worn artefacts in her Swing That Thing project, which aim at extending the body gesturally, mechanically and sensorially, thus encouraging people to move in poetic, expressive and even extra-normal ways, allowing them to perceive and use their bodies from new perspectives. For example, hipDisk (see Figure 6.7 bottom) extends the body horizontally by playing simple sounds in relation to movements of the hips and torso.

Extending the body does not only happen from the outside but can also be obtained from within. Moving towards cyborg relations, technology can also extend our body in new ways that offer us completely new possibilities. Stelarc explores already for many decades what it means to have extra limbs like a third arm [Tofts 2008] (see Web Companion 6.1).

Nowadays we see experiments with various computer chips and sensors in the body for non-medical purposes, e.g. to access public transport [Heffernan et al. 2016]. Or game devices developed in the Exertion Games Lab [Mueller et al. 2020] which explore bodily integrated play, such as the Guts Game [Li et al. 2017], where people swallow a sensor to measure the bodily temperature, which is the interface for the game.

Category 2: Accessing the World

In this section, we describe two types of relationships. The first is centred around technologies that enable people to access the world through their perceptual-motor skills. The second is centred around hermeneutical relationships, where technology needs to be interpreted by people in order to make sense (see Figure 6.8).

Accessing the World Through Our Perceptual-Motor Skills

From an embodied perspective, we skilfully cope with the world, simply because our body, with all its skills, is solicited by the situation at hand and is trying to find maximum grip on the

Figure 6.7 top left: music-touch shoes with three flat micro vibrating motors [Yao et al. 2010]; top-right: wearable soft robotic orthosis [Flechtner et al. 2020]; mid a-e: BioLogic Second Skin [Yao et al. 2015a]; bottom: The hipdiskettes, wearing hipDisk [Wilde 2008];

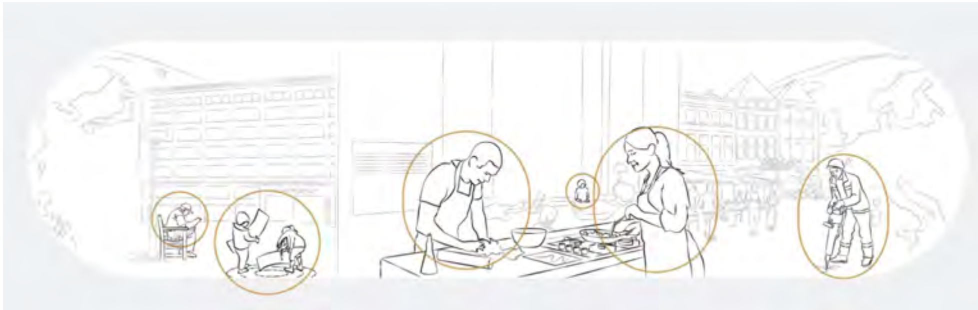

Figure 6.8 Category 2: Accessing the world (picture by Caroline Hummels).

situation [Dreyfus 1996; Merleau-Ponty 1962]. Chairs allow for sitting when people are tired, however, they are supporting toddlers trying to stand and walk. A skateboard is an inconvenient form of transport for some of us, however a skater will continue to see new action possibilities in the world while his skills develop. At first a bench is an obstacle, but while his skills develop, it might become a nice ridge to jump upon. Tangible and embodied interactions offer expressive accessibility to a graspable world in ways that are new and different in comparison to graphical user interfaces, and which potentially allow for physical skill development.

Within the TEI community we see many interactive tables that enhance bodily skills, while giving access to a digital world. For example, in chapter 1 we already showed that URP [Underkoffler and Ishii 1999b] supports the urban planning process by visualising anticipated shadows of architectural buildings on the Sensetable [Patten et al. 2001], and making these concepts easily physically accessible and manipulable. Over the years, the Tangible Media group of Hiroshi Ishii developed many artefacts to realise his vision of Radical Atoms. Through his vision and related devices, he and his team aim to tap into the embodied skills of people, by incorporating the digital into the physical. For example, InForm [Follmer et al. 2013b] was one of the first steps to allow a person to manipulate physical objects at a distance, and with TransForm [Ishii et al. 2015b] he and his team refine the manipulability of interactive physical material (see Figures section 1.3.4).

Examples of artefacts that allows for exploration while moving through space have already been introduced in chapter 3, such as Hydroscope (see Figure 3.14), which enables access to the digital realm through the physical, in this case by allowing children to explore a virtual ocean by moving the big object through space as a mediator between the kids and the virtual ocean [Dindler et al. 2007]. When looking at a bigger urban scale, we have several ways of accessing the world through our perceptual-motor skills. For example, iFloor is an interactive floor that stimulates interaction with the build environment, in this case developed for multi-user interaction in a library context. Due to their urban perspective towards interactive floors, there emerges a completely different relationship with computers as is often the case, one

Figure 6.9 Top: Foxels are smart, modular furniture building blocks that allow owners to customize their own interactive furniture [Perteneder et al. 2020]. Bottom: Station of Being is an innovative bus stop with a smart roof that gently alerts passengers of approaching buses, and rotational shelter pods mounted from the ceiling allowing people to lean comfortably and protect themselves from the wind [RISE and Frieling 2019] (photograph: Samuel Pettersson)

that is incorporating filth, rough use and straightforward cleaning with brushes, which is possible due to the projection technology [Krogh et al. 2004; Petersen et al. 2005]. More architectural examples are Foxels [Perteneder et al. 2020] and Station of Being [RISE and Frieling 2019]. Foxels (see Figure 6.9 top) is a modular smart furniture system developed by the Media Interaction Lab in Austria, existing of different individual snappable building blocks, which support users to create their own preferred interactive furniture with different kinds of functionality [Perteneder et al. 2020]. Station of Being (see Figure 6.9 bottom) is a bus stop in Umeå that is designed by studio Rombout Frieling Lab and Research Institutes of Sweden (RISE) to transform the waiting experience of people in an often cold and snowy

Sweden. The bus stop uses embodiment to elicit a moment of mindfulness, by supporting people to lean against the hanging cocoons and swing themselves. A light and soundscape makes people gently aware that the bus is arriving [RISE and Frieling 2019].

Hermeneutics for Accessing (un)graspable Matter

Next to extending the body and having, e.g., programmable materials to physically interact with, there are many examples of tangible and embodied interaction that focus specifically on extending the mind (which does not imply that other artefacts do not interweave mind and body and (implicitly) extend the mind). As we already explained in chapter 4, when discussing distributed cognition [Hutchins 1996], the representation as well as the computation of information is distributed between brain and the environment. So, people represent information in the world, and they use the world to reason with it and to reduce cognitive load [Kirsch 2010]. This can be done in various ways, by making use of the situatedness and environment to structure our activities, for example, by putting our keys close to the door enabling us to reduce our cognitive load.

Combining embodied relations with hermeneutic relations seems a fruitful and often explored road within the TEI community. Starting from the early days, TEI has been strong in supporting people in embodied and expressive access to and interpretation of data and information. Take for example, the many tools that have been developed to teach children and adults to understand and develop competencies in math, data and computing, and to program without needing to have extensive competencies. For example, the first conference of TEI in 2007 presented two tangible languages to support school children [Horn and Jacob 2007d]: Quetzal for controlling LEGO MindstormsTM robots (see Figure 6.10 top left) and Tern for controlling virtual robots on computer screens (see Figure 6.10 top right). Chapter 2 "TEI In The Wild" discusses several tangible programming tools which can be found commercially, like Little Bits electronic toolkit (Little Bits) and KIBO robotic platform [kin].

Tangible interaction is also used for many other forms of intangibles and abstract concepts. Closely related to these software and programming tools, are interfaces that support data visualisation and manipulation, such as Tangible Query Interfaces (see Figure 6.10 second row right) which offer physical wheels, to represent and manipulate query parameters [Ullmer et al. 2005b]. Nowadays, interactive touchpads with small tokens and interaction tools allow for physical manipulation of data. For example, CoDa (see Figure 6.10 second row left) gives students the possibility to explore and discuss the consequences of statistical findings [Veldhuis et al. 2020]. Other media that are used for tangible manipulation of its various characteristics are, e.g., music and video, with well-known devices like AudioPad [Patten et al. 2006] (see Figure 6.10 third row left) and Tangible Video Editor [Zigelbaum et al. 2007a] (see Figure 6.10 third row right). A canonical tangible interaction example that makes intangible voice messages graspable is the Marble Answering Machine from Durrel Bishop [1992], which is shown in chapter 1 (see Figure 1.7 and 1.7). This tangible interface enables storing of and listening to voice messages, where the marbles both represent the message and act as the control to interact with the message.

Finally, tangible interaction can also be used to express, visualise and interact with complex movements, for example movements of tango dancers which are solidified through MoCap Tango [Peeters et al. 2016] (see Figure 6.10 bottom). Their tango visualisations have various forms and instances, some being expressed real-time on a screen as a background for the dancers, whereas other traces have been 3D printed as solidified movements.

Category 3: Specific Forms of Interaction with the World

During our TEI literature search, we founds several specific forms of interaction with the world, of which we elucidate three in this section. Firstly, there has been a strong and continuous exploration, experimentation and development of various shape changing interfaces and programmable materials over the last few years. Secondly, we like to give a bit more attention to poetical, magical and extraordinary interaction. TEI has always been a very diverse community, where next to developing straight-forward functional technologies, people have been questioning the role and form of human-technology-world relationships through art and design. Thirdly, there has been a serious effort to develop peripheral perception and interaction, as an extension of Weiser's vision of ubiquitous computing [Weiser 1991c]. We will elucidate all three directions in this section (see Figure 6.11).

Shape Changing Interfaces, Programmable Materials

Over the last few years, we see that the interactive technological mediations that are designed to allow people accessing the world around them, are not only making use of screens like URP or the iFloor, but they are getting more and more physically dynamic, like TransForm [Ishii et al. 2015b] which we have discussed in chapter 1. These shape changing interfaces and programmable materials come in all sorts and sizes.

For example, Kas Oosterhuis explored with his architectural design firm ONL and his former Hyperbody Research Group at TU Delft, many buildings, facades and interiors based on Pro-active Architecture (ProA) (see Figure 6.12 top left). These ProA spaces make use of real-time actuated architectural customized components, allowing for interactions that adjust themselves to the situations [Oosterhuis and Biloria 2008].

On a slightly small scale, the Co-motion bench (see Figure 6.12 top right) uses shape changing to stimulate casual interaction and meetings in a public space [Grönvall et al. 2014a; Kinch et al. 2014b]. The LiftTiles [Suzuki et al. 2020] explores an easily adaptable room-scale interior using modular inflatable actuators as building blocks that can change their height from 15cm to 150cm, thus being able to quickly adapt to a preferred situation (see Figure 6.12 bottom).

Even smaller, we discern several different directions of shape-changing interfaces, from bendable screens allowing for more flexibility when interacting and wearing like a watch such

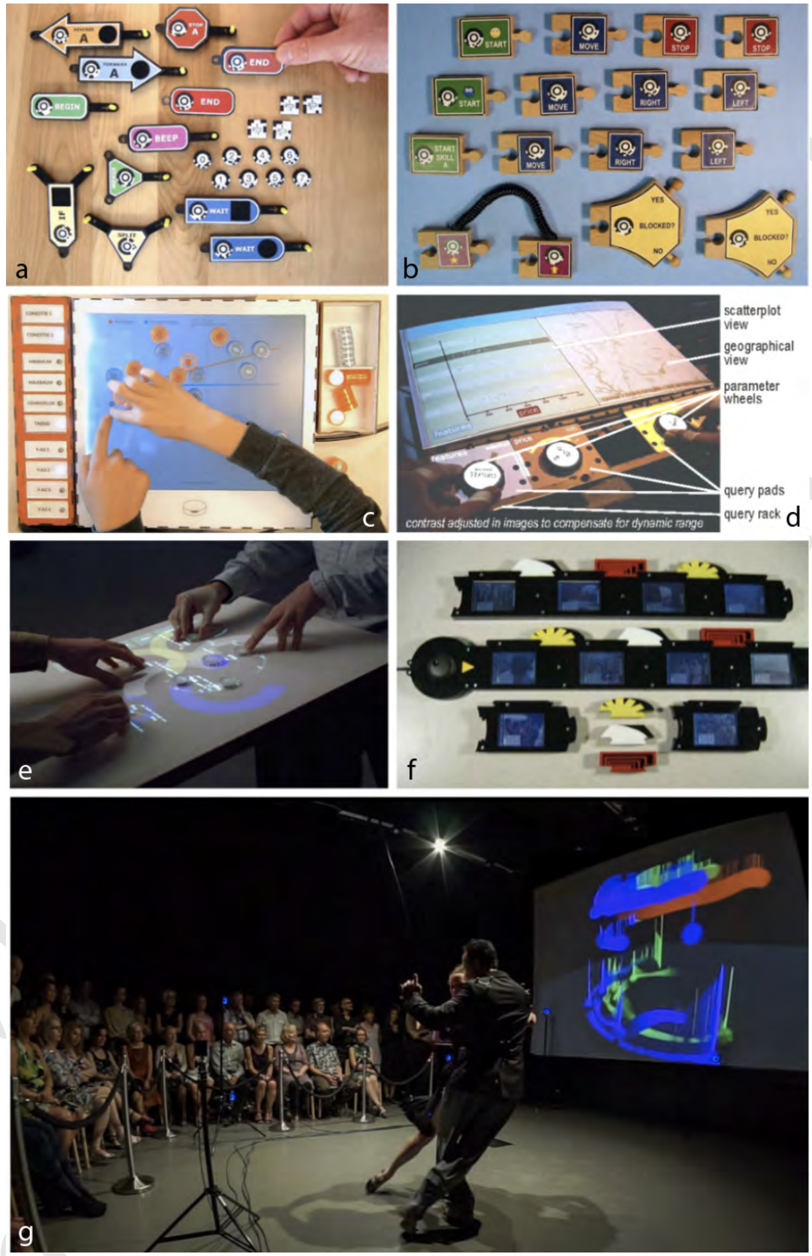

Figure 6.10 Using hermeneutics and embodied cognition to interact with abstract, complex or difficult to grasp matter, for example, a) Quetzal [Horn and Jacob 2006]. b) Tern [Horn and Jacob 2007b]. c) CoDa [Veldhuis et al. 2020]. d) Tangible Query Interfaces [Ullmer et al. 2003c]. e) AudioPad [Patten et al. 2006]. f) Tangible Video Editor [Zigelbaum et al. 2007a]. g) MoCap Tango [Peeters et al. 2016].

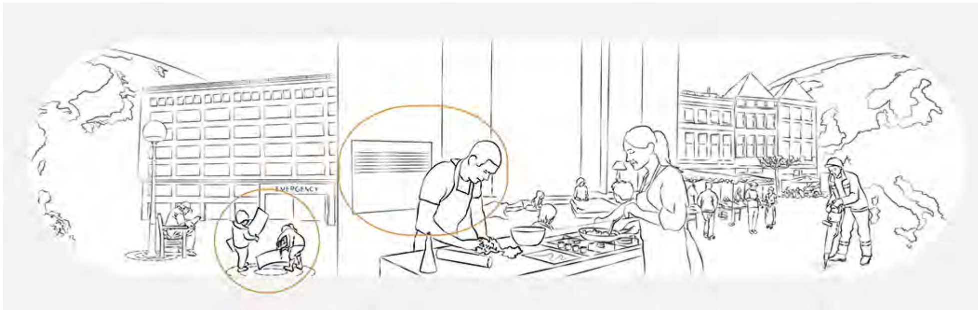

Figure 6.11 Category 3: Specific forms of interaction with the world (picture by Caroline Hummels).

as DisplaySkin [Burstyn et al. 2015] (see Figure 6.12 middle right), to the already earlier shown Biologic [Yao et al. 2015a], which uses Natto cells as small nano actuators to create aesthetically refined shape changing interfaces (see Figure 6.7 bottom). And we see shape-changing interfaces from easily programmable toys like Topobo (see Figure 6.12 middle left) which imitate an initial movement [Parkes and Ishii 2009; Raffle et al. 2004] to physically dynamic and aesthetically refined artefacts such as Ripple Thermostat [van Oosterhout et al. 2018a] (see Figure 6.12 bottom right). Finally, as an exploration to push the boundaries of shape changing materials, we also see attempts to move towards shape changing objects and services through swarms of miniaturised drones. GridDrones [Braley et al. 2018a] is one of the first attempts to move towards programmable materials [Toffoli and Margolus 1991] via very tiny drones.

Poetical, Magical and Extraordinary Interaction

When describing in section 6.2.2 how tangible and embodied interaction can facilitate us to access the world through our perceptual-motor skills, we gave many examples of expressive, functional interactions to support people in everyday life, be it support of their body and bodily skills, functional and expressive, or a combination that also supports embodied cognition. In general, the examples given were focusing on interactions in our everyday life, where some focused on performing a task, while others were more about the experience, being in the moment and enjoying. Even though Station of Being (see Figure 6.9 bottom) is protecting a person against the cold weather in Sweden in the wintertime, the aim of the design was way more focused on the beauty of time, mindfulness and appreciating embodied and situated being in the moment [RISE and Frieling 2019].

A part of the researchers within the TEI community are trying to explore and push the boundaries of interaction toward poetry, magic or the extraordinary. For example, Bert Bongers's installations Tangible Landscapes [Bongers 2020] are composed of a range of interactive audiovisual and sculptural pieces with a high level of engagement and poetry (see

Figure 6.12 A variety of shape changing interfaces and programmable materials, such as, a) The Muscle Body as an example of Pro-active Architecture that is actuated [Oosterhuis and Biloria 2008]; b) coMotion bench to stimulate casual interaction [Kinch et al. 2014b]; c) The Topobo System is a programmable set of toys (courtesy MIT Media Lab); d) DisplaySkin explores the potential of a bendable screen [Burstyn et al. 2015]; e) LiftTiles aim at an adaptable room-scale interior [Suzuki et al. 2020]; f Ripple thermostat offers expressive and aesthetic interaction [van Oosterhout et al. 2018a]

Figure 6.13 Poetical, magical or extraordinary interaction are pursued, e.g., by a) Tangible Landscapes: pumice floating with interactive video display [Bongers 2020] (photo Bert Bongers); b) Tangible Scores [Tomás 2016]; c) Aerial Tunes [Alrøe et al. 2012]; d) Pillow, raising awareness of the local electroclimate, part of Hertzian Tales (1994-97): [Dunne and Gaver 1997].

Figure 6.13 top left). They enable people to explore abstract landscapes of nature shown via movies, through interacting with found materials in nature like stones, leaves and glass. Tomás [2016] explores how a connection can be made between artistic expression and physicality, connecting music and scores via vibration and tangibles, which has resulted in Tangible Scores (see Figure 6.13 top right). With his study, Tomás explores the concept of *"performative materiality"*, where tangible musical instruments can be interpreted as scores. Another example, which is giving a magical feeling, is developed by Alrøe et al. [2012]. Their installation called Aerial Tunes (see Figure 6.13 bottom left) lets six white balls hover steadily in mid-air. Rasmussen [2013] describes how technology can create the impression of a magical interaction, based on the four types of magical casualties as described by Subbotsky [2010]: mind- over-matter magic, animation magic, non-permanence magic and sympathetic magic. Companies like Bang and Olufsen have always been fascinated by magical experiences, and exploring these based on ingredients like surprise, the unordinary, the unnatural or the exciting [de Jongh Hepworth 2007].

Although developed as a critical design, Pillow, created as part of Herzian Tales by Tony Dunne [2008] (see Figure 6.13 bottom right), opens up a new imaginative, magical and until now invisible world which might evoke *"wonderment rather than shock"* Dunne and Gaver [1997]. Dunne's devices enable people to get access to perceptions of electromagnetic fields they could not have before. Pillow incorporates a manipulated LCD screen that responds to ambient electromagnetic radiation by showing changing light patterns, thus inviting people to reflect on and make sense of this radiation, including questioning topics such as privacy. Apart from emphasising aesthetics instead of mere usability, Pillow also raises *"deep questions about the meaning of digital media and in suggesting alternatives to our current assumptions"* [Dunne and Gaver 1997]. The latter will be more extensively addressed in category 6: socio-cultural debate and speculation.

Peripheral Perception and Interaction

Almost opposite to poetical, magical and extraordinary interaction is peripheral interaction. In most examples explained in the above sections is the interaction and device at the core of our focus when engaging with the world. However, the field of TEI is strongly related to Weiser's vision of ubiquitous computing, where computing technology is integrated in our everyday environment and routine, and is generally not at the core of our attention [Weiser 1991c]. In 1997, Weiser and Brown coined the term calm technology "which engages both the center and the periphery of our action, and in fact moves back and forth between the two" [Denning et al. 1997]. One of the first canonical examples is Natalie Jeremijenko's Dangling string (described in Weiser and Brown [1996c]), a plastic string that is attached to an electric motor mounted to the ceiling. Whenever information passes the nearby Ethernet cable, the motor gives a tiny twitch causing the string to 'dance' in relation to the data traffic. More than 10 years later in 2006, the Power Aware Cord (see Figure 6.14 middle right), is doing a similar job for electricity, which next to functionally transporting electrical power, visualizes energy usage using the flow, intensity and pulsation of light [Glynn 2006; Gustafsson and Gyllenswärd 2005].

Another example of peripheral visualisation is Sidetrack, a small round table displaying the movement pattern of a person working at home, when he or she moves from one space to another [Barcikowski et al. 2010] (see Figure 6.14 middle left). A bigger ambient display taking up a whole room is Pinwheels (see Figure 6.14 top), developed by Hiroshi Ishii and his students to display ambient information such as stock market activity or natural wind movement, spinning like a wind of bits [Ishii et al. 2001b].

Saskia Bakker extended the notion of peripheral perception to peripheral interaction, also to extend the concept of calm technology, which often refers to a specific, quiet and serene type of perception and interaction in everyday life. Peripheral interaction can be placed in a messy

Figure 6.14 Various examples of peripheral perception and interaction, for example, a) Pinwheels, displaying ambient information (courtesy MIT Media Lab); b) Sidetrack, visualizing people's movement patterns [Barcikowski et al. 2010]; c) Power-aware Cord, visualizing energy usage [Gustafsson and Gyllenswärd 2005]; d) FireFlies for communication at primary schools (photo Saskia Bakker).

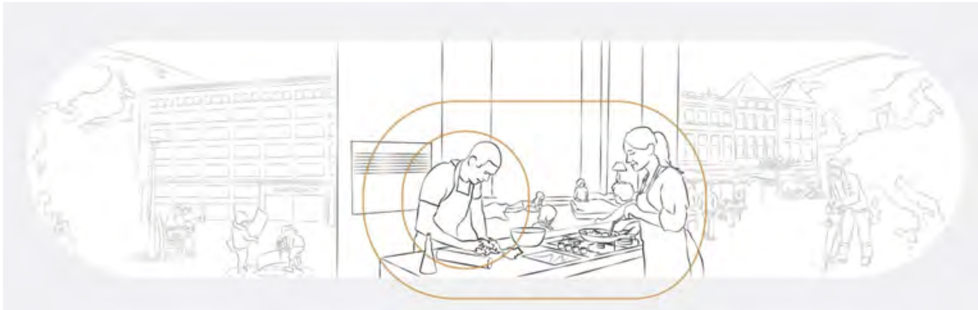

Figure 6.15 Category 4: Empowering and expressing ourselves in our socio-cultural context (picture by Caroline Hummels).

and turbulent environment, with the purpose of switching between the periphery and focus of attention when needed [Bakker et al. 2012]. Bakker's FireFlies is an open-ended system that allows primary school children and teachers to communicate with each other in a peripheral way. The small FireFlies light-objects and the FireFlies Teachers-tool allowed children and teachers to quickly and frequently interact, without disturbing the rest of the class (see Figure 6.14 bottom).

In the previous sections, we saw several examples of designs that use their physical qualities to facilitate and enhance social interaction, like URP and FireFlies. In the following sections, we discern a few specific relations and purposes that tap into the different aspects of social interaction. We start with an overall category of empowerment of people in their socio-cultural environment, followed by expression of self and groups, and interactions that stimulate collaboration and interaction with others, including large groups. We conclude this part with a last category that looks at stimulating socio-cultural interaction through art, debate and speculation.

Category 4: Empowering and Expressing Ourselves in Our Socio-cultural Context

In this section, we describe two types of relationships. The first is centred around empowerment of individuals in their socio-cultural environment and the second is centred around the expression of self and groups (see Figure 6.15).

Empowering People

People appropriate and use technology through which they access and constitute the world, and vice versa, the world and technology are also constituting us [Ihde 1995; Rosenberger and Verbeek 2015a]. For example, through nowadays technologies like GPS and the internet we can have access to (almost) the entire world 24x7. Simultaneously, this means that the world is pushing us towards this 24x7 digital-physical realm. It sometimes feels as if the world is expecting our availability 24x7. And in case people do not have the means or the skills to interact with this digital realm, they might even get excluded.

Because of its physical and social situatedness, the realm of tangible and embodied interaction offers, in principle, many opportunities for empowering and respecting people, involving them, and enabling them to have meaningful interactions.

Tangible and embodied interactions can be used to empower people being themselves, creating their own meaningfulness, exploiting their own skills and cognition, and allowing them to interact with people and a world that fits their being in the world.

For example, instead of seeing people on the autistic spectrum as challenged or handicapped, Jelle van Dijk and his students [van Dijk and Hummels 2017] developed MyDayLight, to enable them to life independently, support their competencies, values, and take on life as well as supporting them to interact with their social environment (see Figure 6.16 left). MyDayLight is enabling people on the autistic spectrum to structure their life within the situatedness of everyday living at home, using situated guiding light bulbs next to a tablet with a calendar and tasks. The entire system is owned by its user, giving him full control, which was not the case with the existing devices. For example, MyDayLight facilitates its user to invite his counsellor into his house, who supports him to structure his life.

LinguaBytes developed by Bart Hengeveld has a similar starting point towards multi-handicapped toddlers to support them in their self-confidence and joy in life, for which language is an important ingredient (see Figure 6.16 right). It is not just about learning to communicate and speak, also the way this is done is very important. LinguaBytes makes use of interactive stories and a large set of small representations, allowing the toddlers to learn language by making stories and doing assignments with help from their peers and teachers [Hengeveld et al. 2013a]. Both examples, MyDayLight and Linguabytes, show a deep understanding of their user group and were developed in close cooperation with their stakeholders in order to be able to reach empowerment on all levels, cognitively, perceptual-motor, emotionally and socially.

Jelle van Dijk, Assistant Professor at University of Twente

I am a design-researcher trained as a cognitive scientist. I see the field of tangible and embodied interaction as a fantastic opportunity to investigate the way human beings interact with the world, especially regarding recent theories of embodied sensemaking. While many designers are keen on using cognitive theory as inspiration to their design, I have always pointed out that this design field embodies, in my view, a much richer goldmine than purely investigating various forms of human-technology interaction. Embodied technologies can actually be used to investigate fundamental theoretical notions about the embodied nature of human being-in-the-world. The phenomenological investigations of Maurice Merleau-Ponty tell us how the lived body anchors our ‘being-in-the-world’. And

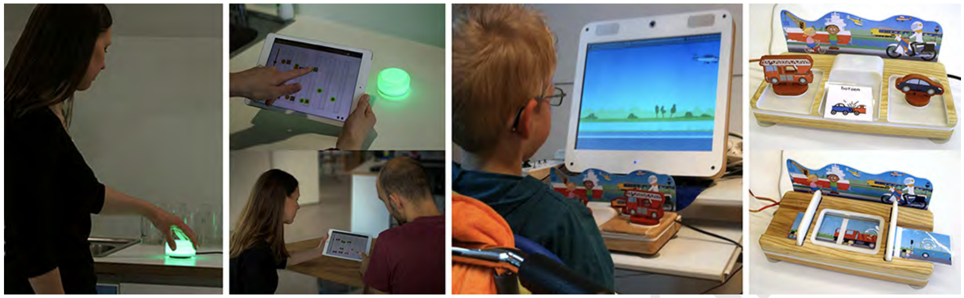

Figure 6.16 MyDayLight supports people on the autistic spectrum to structure their own life (left) [van Dijk and Hummels 2017] and Linguabytes supports multi-handicapped toddlers to learn how to communicate while supporting their self-confidence (right) [Hengeveld et al. 2013a].

embodied cognitive science has identified how external artifacts may be incorporated in our bodies, augmenting and sustaining our sensemaking practices. But these ideas are far from fully developed. Moreover, mainstream experimental psychology has a hard time diving into these matters because much of embodied interaction has to do with context and situatedness, which is difficult to investigate in a laboratory setting. I believe exploring and reflecting on the design of interactive technologies can be used as a method to complement traditional cognitive science and experimental psychology. In my work I have been trying to pinpoint various scaffolding roles that interactive artifacts may come to play in everyday human sensemaking activities, by designing new interactive forms, together with diverse user groups, for various concrete realworld settings. In the past years I have focused on young autistic adults who are living semi-independently and wish to become more independent. Autistic people experience the world in a radically different way than do non-autistic people. Traditionally, assistive technology designed for autistic people has progressed from a medical, disability model, and it aims at training autistic children to adhere to majority social norms or to compensate for their 'deficits'. Instead, my focus is on designing embodied technologies that enable autistic people to develop a stronger grip on their own lives and make sense of their lifeworld, in a way that is beneficial to them, and starting from their own, personal normativity. This may lead to tools and artifacts that would make little sense to non-autistic people, because they are designed to become appropriated into a fundamentally autistic way of 'being-in-the-world'. My project aims to empower autistic people to be and develop themselves - over and against this largely non-autistic world they have to cope with - as well as to help non-autistic people, through the appreciation of these design projects, to understand autism from a new perspective: Less as a disability or problem, and starting from acknowledging the rich diversity of ways people can be in and make sense of the world.

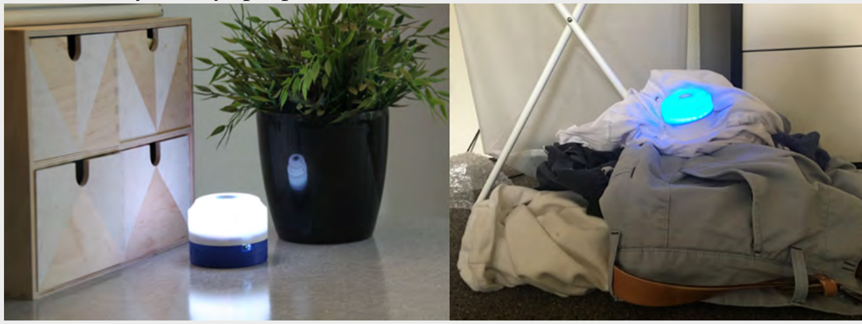

Figure Left: MyDayLight, wireless luminous objects help organise and execute daily activities (photo Laura Beunk). Right: MyDayLight in use in a facilitated living apartment by a young autistic man (photo Niels van Huizen).

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Expressing Ourselves and Connected Socio-cultural Realms

We live in a world surrounded by others. Technology in all forms, from low-tech to high tech, allows us to relate ourselves to others through our expression. For example, there is a long history of fashion which allows people to express themselves. Within the TEI community, this expressive mode of textiles was brought to the interactive realm through so-called wearables. In the Wearable Senses (WS) lab at the TU/e in Eindhoven, they focus on *designing close-to-the-body interactions, specifically designs that incorporate wearable computing or smart textiles"* [Tomico et al. 2014]. Part of their designs focus on category 1, sensing and extending the body, for example Vibe-ing that uses vibration therapy for self-care (see Figure 6.17 top left, right dress). But a large part of their designs also supports people to be empowered and express themselves, like these designs on the left in Figure 6.17 (top left).

Another example of one of the many designs in the worldwide field of wearables that is designed to express oneself is Monarch (see Figure 6.17 middle left). Monarch is a muscle-activated kinetic textile that can be both used to express oneself as well as feel as a visceral extension of self [Hartman et al. 2015]. Young Suk Lee explored the possibilities of an interactive wig called Thou and I to express oneself towards others [Lee 2018] (see Figure 6.17 top right). Of course, we do not only express ourselves through wearables or our own body, but also through interactive jewelry and various other artefacts from small to large to express ourselves and our values, as can be seen throughout this book.

When looking at dance, tangible and embodied interaction can also add an extra layer of expression. For example, NUVE projects a virtual double, allowing the dancer to have a digital performance and interact with his own digital virtual body [Martinho Moura et al. 2010] (see Figure 6.17 bottom left).

Technology does allow us to express ourselves as unique individuals, but also to stress our belonging to a social-cultural setting and community. For example, Wo.Defy refers to the suffragette North Cantonese Chinese women of the late 19th and early 20th century, who used a different kind of hair-styling and dress to challenge the traditional marital status of women [Schiphorst et al. 2013] (see Figure 6.17 middle). Wish Happiness is inspired by Tibetan Mahayana Buddhism, aiming to research ritual interaction to stimulate the cultivation of compassion [Mah et al. 2020] (see Figure 6.17 middle right). Finally, we also see examples of religious expression, like the interactive prayer nuts, which are a multimodal ensemble of interactive objects that trigger visual, aural, tactile, and olfactory interactions [Kwan et al. 2016] (see Figure 6.17 bottom right).

Category 5: Social Interaction

Next to empowering people in their social context and stimulating them to express themselves and their connected socio-cultural realm, we also see a large group of tangible and embodied interactions that stimulate social engagement and collaboration with others, including large groups. In this section, we address these relationships, referring to interaction with people as well as animals and nonhuman intelligent entities (see Figure 6.18).

Interacting and Collaborating with People and Beyond

Throughout this book, you can spot many interactive tables, which are developed for collaboration in various way, be it to discuss and explore urban planning like URP [Underkoffler and Ishii 1999b], visualizing business supply chains with Sensetable [Patten et al. 2001], or creating music with Reactable from Jordà et al. [2007b]. Next to interactive tables, their have been many tangible and embodied designs specifically designed to stimulate social interaction and collaboration with small and large groups of people. In this section we will introduce a few examples to exemplify the specifics and subtleties of social interaction.

In 1996, Rob Strong and Bill Gaver developed Feather, Scent and Shaker, tangible interfaces to communicate implicitly and expressively one's presence with love-ones at a distance with minimal means [Gaver and Strong 1996] (see Figure 6.19 top left). Their approach collided with and sparked many other expressive forms of communication at a distance such as InTouch developed at MIT Media Lab [Brave et al. 1998a] (see Figure 6.19 top right).

[Mitchell et al. 2017a] explored in their studio at TEI17, how technology can share or transfer embodiment between two or more people. They discussed, for example, Parallel Eyes, where people can see the first person videos from the three participating people, next to their own [Kasahara et al. 2016a]. Moreover, they introduced BioSync, which uses the

Figure 6.17 Various designs enabling people to express themselves and connect to their socio-cultural realms, for example, a) Oscar Tomico standing amidst various designs from Wearable Senses at TU/e; b) Young Suk Lee wearing her interactive wig Thou and I [Lee 2018]; c) Monarch, supporting the feeling of a visceral extension of self, next to expressing oneself [Hartman et al. 2015]; d) Wo.Defy, referring to the suffragette North Cantonese Chinese women [Schiphorst et al. 2013]; e) Wish Happiness to cultivate compassion [Mah et al. 2020]; f) NUVE, enabling dancers to interact with their own digital virtual body (courtesy João Martinho Moura); and g) Interactive Prayer Nuts [Kwan et al. 2016].

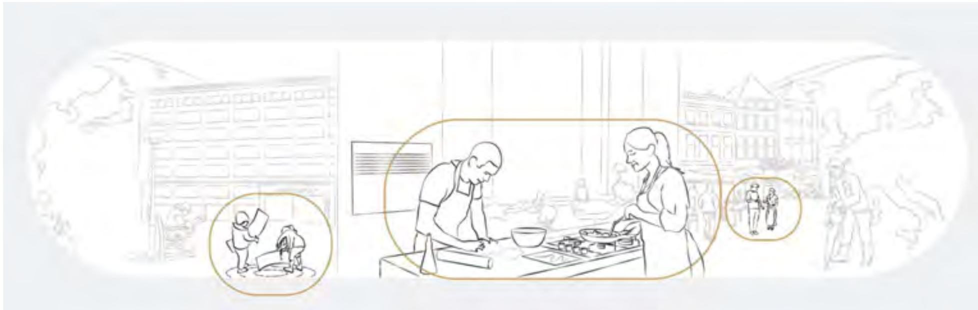

Figure 6.18 Category 5: Social interaction (picture by Caroline Hummels).

possibilities of biosignal driven electrical muscular synchronization to enable kinesthetic exchange (see Figure 6.19 middle left). This kinesthetic swapping, allows, for example, healthy people feeling the tremors that Parkinson disease patients experience [Nishida and Suzuki 2016a]. Related exchange of experience is done by [Smeenk et al. 2018] with Into D'mentia, a tangible environmental simulator to let people experience subtle situations that are based on the everyday reality of people with dementia. [Pratte et al. 2021] give an overview of so-called empathy tools, which enables developers and users to be placed in someone else's world, as close as possible to that person's lived and felt experience, in order to evoke empathetic responses.

Instead of feeling a connection and engagement with one person or a specific group of people, Stoffel Kuenen focused in his PhD thesis "Design and aesthetics of being together" on physical engagement and connection with multiple people (up to large groups) at the same time, e.g. using his designs Sliders and DiffractMe! [Kuenen 2018; Peeters et al. 2014] (see Figure 6.19 bottom right). Next to creating this felt connection with multiple people, artefacts and spaces are also developed to strengthen collaboration. For example, The Blue Studio is an interactive space with interactive objects to support a multi-stakeholder team designing innovative embodied propositions [Jaasma et al. 2017a] (see Figure 6.19 middle right).

Tangible and embodied interaction does not only enable us to connect to and collaborate with other persons, it can also be used to connect to other entities like animals or intelligent artefacts. For example, Hou et al. [2017a] developed the co-op game Human and Dog, which lets one of the players step into the perspective of a dog, thus exploring unequal communication. Now that interactive devices and spaces move more and more towards intelligent and autonomous devices and spaces, it can spark a whole new category of devices that enable people to interact expressively with their smart environment. This will partly be done via shape changing interfaces that are an inseparable part of the smart device or environment, like the examples given earlier in that specific section. It might also imply that we will have separate tangible devices to communicate expressively with smart devices and environments. For ex-

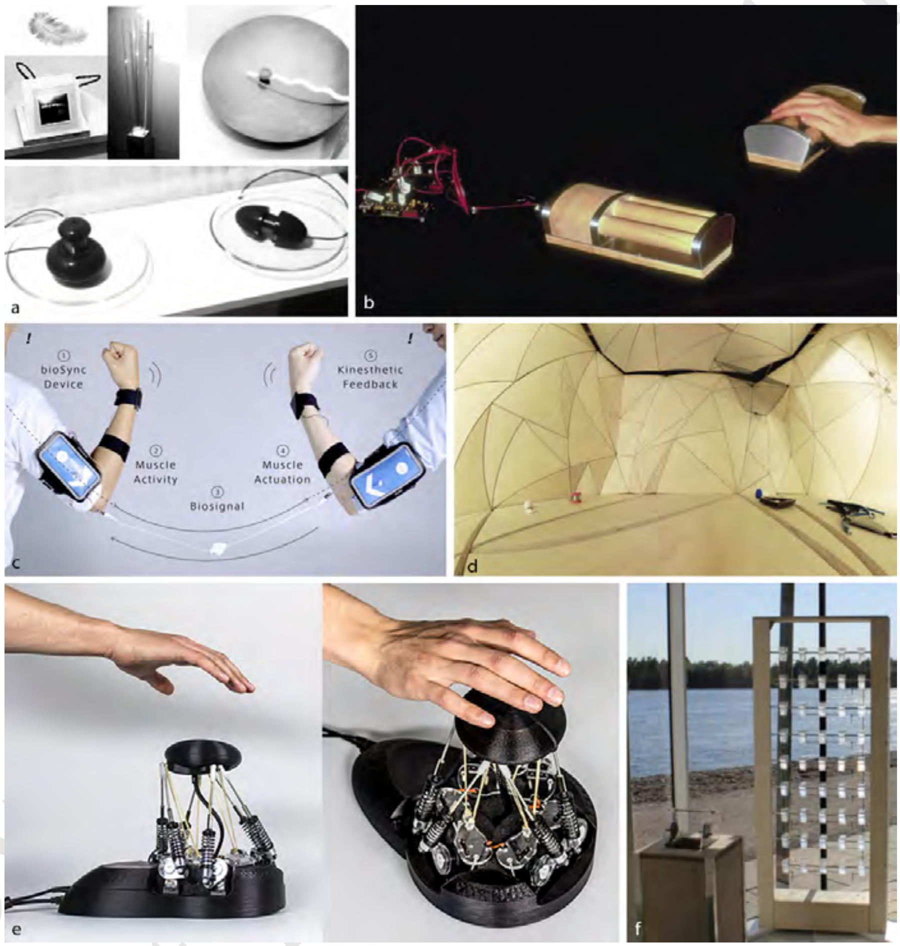

Figure 6.19 Various examples of artefacts that support interaction and collaboration with people and environments, such as a) Feather, Scent and Shaker [Gaver and Strong 1996]; b) InTouch (MIT); c) BioSync (courtesy MIT Media Lab); d) The Blue Studio [Jaasma et al. 2017a]; e) Stewart (Photos by Felix Ros) [Terken et al. 2016]; f) DiffractMe! [Peeters et al. 2014].

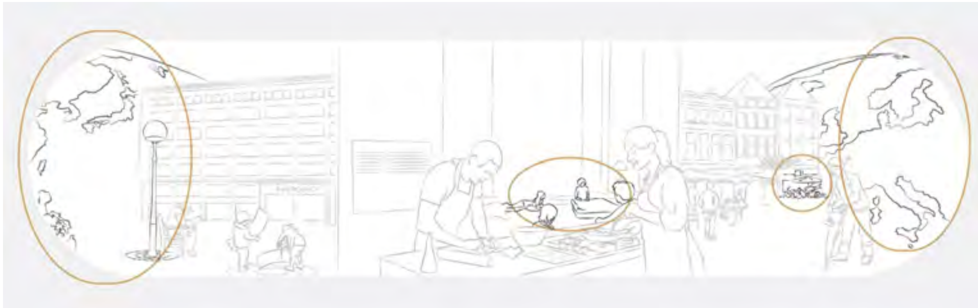

Figure 6.20 Category 6: Socio-cultural debate and speculation (picture by Caroline Hummels).

ample, Stewart, designed by Felix Ros, allows a person to interact with his self-driving car as an expressive perceptual-motor dialogue to anticipate traffic [Terken et al. 2016] (see Figure 6.19 bottom left).

Category 6: Socio-cultural Debate and Speculation

We conclude this entire overview of possibilities of purposes of TEI, with a last category that looks at stimulating socio-cultural debate and speculating about (non-) preferred (critical) futures (see Figure 6.20).

Addressing socio-cultural issues via art and debate

Whereas the previous section focused on empathising and collaborating with people, be it an individual or a group, tangible and embodied interaction can also explicitly question and explore socio-cultural issues. As of the start of this community and series of conferences, art has always played a prominent role in TEI. Several examples of social-cultural critique and debate, like Pillow Dunne [2008], have already been touched upon in the above-mentioned sections. In this section, we will introduce a few additional examples. For example, at the first TEI conference in 2007, The Meatbook made quite an impression (see Figure 6.21 top left). It is an interactive art installation where an animal heart was mechanically animated, thus provoking a visceral response of the person viewing or touching (depending on his courage) that was generating both revulsion and fascination [Levisohn et al. 2007]. Meatbook explores the boundaries of the materials used for tangible interaction and by bringing an animal heart to life it sparks also the discussion on a posthuman area. Also Ballade of Women (see Figure 6.21 top right and bottom) is an interactive art installation, although with a completely different scale and topic. It explores different perspectives on women's rights, more specifically how ancient paintings from the 15th, 16th and 17th Century, put in today's context, can spark a debate about emancipation, self-determination and violence [Marti et al. 2015].

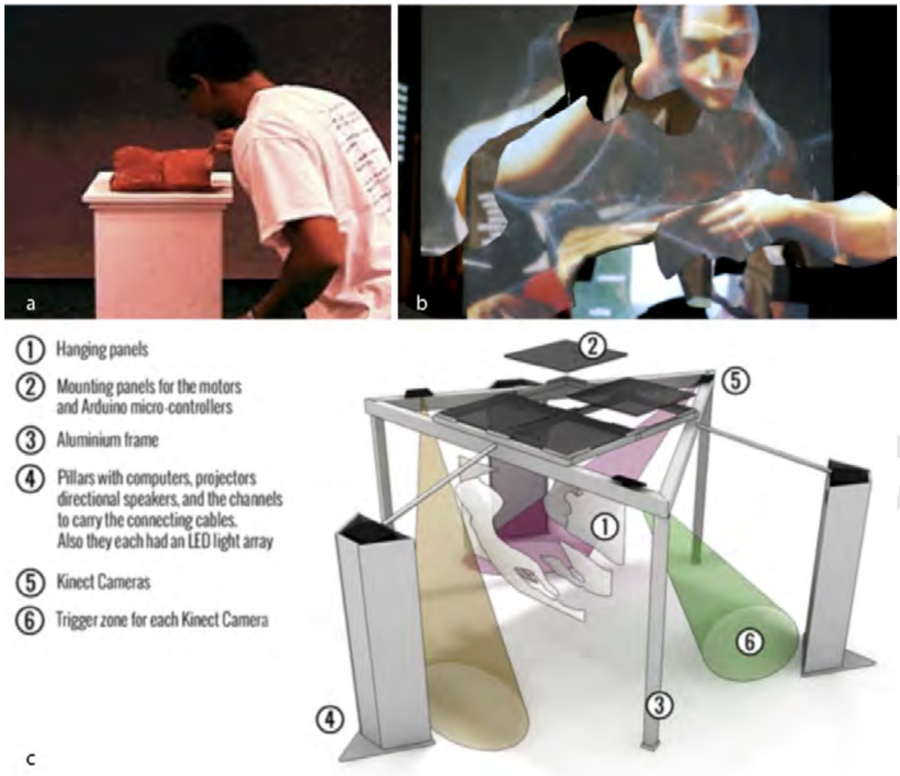

Figure 6.21 Addressing socio-cultural issues via art and debate, for example via a) MeatBook, discussing a posthuman area [Levisohn et al. 2007]; b+c) Ballade of Women, discussing emancipation, self-determination and violence (Photo top right: courtesy Patrizia Marti; illustration bottom: RISE).

Speculative Design, Critical Design and Design Fiction

A specific form of debating and criticizing society is done through speculative design and its relatives such as material speculation, critical design and design fiction, focusing on designing future interactions to question our current and future realms. For many decades, speculative and fictional approaches have been used to explore human-computer interaction. For example, using personas is deeply interwoven in a user-centred approach after Cooper [2004] introduced the concept to describe fictitious users. And also the use of scenarios is widespread in our community for many decades [Carroll 1997; Young and Barnard 1986]. For many years, the HCI community focused on fictional scenario, concept and story-based futures, where design fictions can be regarded as representations of futures from science fiction that are captured in design scenarios specifying people, practice and technology in this future [Bell and Dourish

2007]. The artifacts developed in these design fictions are generally references, props or non-functioning prototypes, which Kirby [2010] also refers to as diegetic prototype, i.e., an artefact that only exists and functions in that future fictive world. For example, Leonardo Bonanni created with Hiroshi Ishii and his team the scenario of Perfect Red, a shape-memory clay to give substance to the Radical Atoms vision [Ishii et al. 2012c] (see Figure **??** top left). Cheung and Antle [2020] studied and analysed imaginative systems in Science-Fiction movies in relation to tangible user interfaces and the MCRpd interaction model [Ullmer and Ishii 2000b], and they show the wide-spread use of tabletop systems that support physical manipulation, e.g. shown in the movies Black Panther [bla 2018] and Iron Man [iro 2008].

Next to these scenarios and more prop-like prototypes, there have been several designers and researchers that created speculative working artifacts, with the purpose to include people in the critical debate via objects displayed in, e.g. museums and exhibitions. For example, Dunne and Raby introduced the concept of physical fictions and developed many prototypes to debate e.g. a fictional future for the United Kingdom, called United Micro Kingdoms [Dunne and Raby 2013a] (see Figure **??** bottom left). Over the last years, we see a rise in more speculative approaches that are still future-oriented but which create and use actual working artefacts to be used in the here and now to critically question our assumptions regarding design and technology [Wakkary et al. 2015a]. These speculative and critical design approaches aim at exploring and questioning possible, plausible, probable, and preferable futures [Hancock and Bezold 1994] by making them experienceable, so-called material speculation [Wakkary et al. 2015a]. In a way, the Placebo Project from Dunne and Raby, makes this step from the museum to the home context, when they decided to distribute their prototypes via the Victoria & Albert museum, in a special department store's window display and advertised through a national newspaper, to have people experience these Placebo designs at home [Dunne and Raby 2002] (see Figure **??** top right). Wakkary and his team develop material speculations and counterfactual artefacts like the Table-non-table and Tilting Bowl to explore their impact in the everyday environment [Hauser et al. 2018b; Wakkary et al. 2018a] (see Figure **??** bottom right).

The Person(s) Interacting

Since we consider aesthetics not merely to be a property of the artefact, but created in a social-cultural setting through use and appropriation of the artefact, we discuss in this section how the values, skills, and human body open up a design space for tangible and embodied interaction.

Values

Dourish [2001c] indicated the importance of meaningful interaction. Others have coined terms like participatory sensemaking [Jaegher and Paolo 2007] to stress the importance of the situatedness to create meaningful interaction. Apart from being meaningful in a practical way, we consider it also important to look at the underlying values for and of interaction which can

Figure 6.22 Examples of speculative design, critical design and design fiction, including a) Perfect Red, a shape-memory clay giving body to the Radical Atoms vision [Ishii et al. 2012c]; b) Placebo Project (2001) - the Nipple Chair Nodules embedded in the chair's back vibrate when radiation passes through the upper body of the seated person (photo Jason Evans) [Dunne and Raby 2002]; c) The Communo-nuclearist society is one of the four fictional futures for the United Kingdom, United Micro Kingdoms, 2012/13 (GI: Tomasso Lanza) [Dunne and Raby 2013a]; d) Table-non-table, a slowly moving stack of paper used to research artefacts as a resource for creative use and reuse [Hauser et al. 2018b]

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determine the type of interaction a person prefers. If a person is creative and seeking openness and change in life in a hedonic way, he might prefer to interact in a completely different way than a person seeking for power and authority, or a person valuing benevolence and tolerance. Having a fit between the values people have or pursue and the values addressed and supported while interacting with a new tangible or embodied device, can increase the success of the device.

Schwartz [2017] developed over the last 25 years his refined theory of basic values, which can support designers to tune their type of interactions. Schwartz discerns 19 values, which are classified in different sections. In general Schwartz sees two dichotomies, anxiety-free people who value growth (AF) and anxiety-avoidance people who value self-protection (AA). Moreover, people can be more personal focused (PF) or social focused (SF). Within these boundaries, he discerns four main categories which contain the 19 different values [Schwartz 2017]:

1. *People valuing openness to change (AF, PF):*
   - Self-direction, i.e, Thought and Action: freedom to determine one's own thoughts and actions
   - Stimulation: Seeking for excitement, originality, and change in life
   - Hedonism: pursuing a pleasurable life with sensuous fulfilment
2. *Self-transcendence (AF, SF):*
   - Benevolence, i.e, Dependability and Caring: Being a responsible and reliable member of the community, committed the wellbeing and welfare of other community members
   - Universalism, i.e, Tolerance, Concern and Nature: Understanding and accepting others who differ from us, being dedicated to equality, fairness and protecting others and nature.
   - Humility: Acknowledging one's insignificance in relation to others and the world
3. *Conservation (AA, SF/PF):*
   - Humility: Acknowledging one's insignificance in relation to others and the world.
   - Security, i.e, Personal and Societal: Ensuring safety and stability in one's personal life as well as in society as a whole.
   - Conformity, i.e, Rules and Interpersonal: Obeying rules, regulations and formal obligations, and avoiding to distressing or harming others.
   - Tradition: Maintaining and preserving traditions such as cultural, family and religion.

- Face: Having and maintaining your own image or identity towards others and not being humiliated by others.

4. *Self-enhancement (AA/AF, PF):*
   - Face: Having and maintaining your own image or identity towards others and not being humiliated by others.
   - Power, i.e, Dominance and Resources: Having control over others and over situations via materials and social resources.
   - Achievement: realising success according to social standards.
   - Hedonism: pursuing a pleasurable life with sensuous fulfilment.

When looking at examples of tangible and embodied interaction, some values like hedonism and stimulation seem to have been upgraded to application areas, in this case gaming and playful interaction, such as the Swallow example [Mueller et al. 2020] that was discussed earlier. Many other researchers have been inspired to develop devices to support specific values, as also shown in section 6.2. The tradition of prayer nuts has for example been captivated and enhanced via values such as tradition and perhaps humility [Kwan et al. 2016] (see Figure 6.17). Security has been addressed in many different ways such as keeping one's body safe with, for example, the wearable soft robotic orthosis [Flechtner et al. 2020] (see Figure 6.7).

But values can also be a starting point for designing everyday tangible and embodied interactions with a specific flavour. Even more so, technology is never neutral and always expressing and evoking certain values while reducing others. In the previous sections, we have seen many examples of designs evoking certain values while reducing others. For example both Feather, Scent and Shaker [Strong and Gaver 1996] as well as InTouch [Brave and Dahley 1997a] stimulate connection and closeness to another person, captured best by Benevolence in Schwartz's overview (for both see Figure 6.19). However, the way they do this is quite different. Whereas Feather, Scent and Shaker seem to offer expressive diversity through hedonism and stimulation, InTouch seems more introvertedly focusing on the tactile subtleties, being closer to self-transcendence, with perhaps even a touch of conservation.

Perceptual Motor, Cognitive, Emotional and Social Skills

When designing tangible and embodied interaction it is important to be aware of the full spectrum of skills people have in order to enlarge the design space. Overbeeke et al. [2004] and Stienstra [2016] consider four types of skills when designing for embodied interactions: perceptual-motor, cognitive, emotional and social skills, which are all interdependent and part of our overall embodied system. Let's us address these four skills briefly in the light of TEI.

Perceptual Motor Skills

Perceptual-motor skills, also addressed by others as sensorimotor skills, refer to our skills of sensing the environment like seeing, hearing and smelling, as well as moving and acting within the environment, such as moving, touching and making sound.

Tangible and embodied interaction have been predominantly focusing on touch, movement, kinesthetics, vision and audio, as most examples in this book show. Often these senses seem to be taken for granted, and it is not often elucidated why a specific sense modality would be the best way for giving feedback.

However, there are a few exceptions, especially researched by Obrist et al. They wrote several papers on less or rarely often used sense modalities in human-computer interactions, more specifically smell [Obrist et al. 2014b], taste [Obrist et al. 2014a] and tactility and touch, including temperature, surfaces and pressure [Obrist et al. 2013].

Tangible and embodied interaction often make use of the combination of different sense modalities, also called multi-sensorial design [Schifferstein and Spence 2008]. The phenomenon of synaesthetic experiences might be helpful to refine and strengthen these combinations. Synaesthesia is combining several sense modalities, such as seeing colours when hearing music, or seeing form and movement when smelling a certain odour. For example, [Hummels et al. 2007] found in an experiment a strong link between odour, form and movement, operationalized by letting designers and dancers gesture/dance expressive shapes based on different scents, and thereupon, having an illustrator/designer sketch objects based on black and white movies of these gestures and dances (see Figure 6.23). In a matching experiment, participants were significantly able to correctly map the different stimuli. Moreover, the resemblances between movements, forms and scents were remarkable, and clear expressive groups were discernible.

Although most people do not have an absolute relation to synaesthesia, the principle does help in developing multi-sensorial devices and has been used for multiple tangible and embodied interactions. For example, hipDisk [Wilde 2012] makes a connection between body gestures and sounds (see Figure 6.7 bottom). SoLu hyper instrument, designed by 3kta makes multisensorial compositions based on the combination of light and sounds [Macedo and Siegel 2010] (see Figure 6.24 top left). PinchPad [Wolf et al. 2012] is developed to use touch-based gestures to get a rich multi sensorial experience (see Figure 6.24 top right). And Sensory VR tries to enhance the users experience by letting them stand on different textures such as sand or grass [Harley et al. 2018] (see Figure 6.24 bottom).

Emotional Skills

Emotions colours people's being in the world, their behaviour, their thoughts, their motivation, their connection to others etc. Their emotional skills enable people to feel while interacting in the world. It allows for appreciation of the expressiveness of artefacts and the environment

Figure 6.23 There seems to be a strong link between odour, form and movement, as show in an experiment by [Hummels et al. 2007]. For example, one of the dancers expressed the scent ‘Ligustral’ in a dance (left), and the black and white movie of her dance was captured by an illustrator/designer in a drawing of an object (second left). Both the dance and the object resemble the gestures and sketch made by one the design students based on the same scent ‘Ligustral’ (middle and second right). Moreover, the drawing made ny the external illustrator/designer, based on a black and white movie of the students’ gestures, is related both in form and colour (right). All three drawings of sculptures are highly similar with respect to shape and colour. This is all the more striking, because the illustrator/designer worked with black and white movies [Hummels et al. 2007].

Figure 6.24 Devices making use if multi-sensorial interaction, such as, a) SoLu Hyperinstrument by 3kta; b) PinchPad [Wolf et al. 2012]; c) Sensory VR [Harley et al. 2018].

surrounding them. It supports people to express themselves. The expression “being moved” shows the strong link between emotional skills and movement, stressing another potential strength of tangible and embodied interaction.

There are dozens of emotions people can have and feel, and several frameworks and models explain the possibilities and relationships, such as Plutchik’s wheel of emotions [Plutchik 2003], showing 8 primary emotions, i.e., joy, trust, fear, surprise, sadness, disgust, anger and anticipation. Or the ‘circumplex model’ of affect from Russell [1980], which is based on two dimensions: valence and arousal. These dimensions connect strongly to Osgood’s factors of semantic meaning [Osgood et al. 1957], more specifically evaluation and activity. Valence / evaluation are linked to human judgement and correlating with pleasant - unpleasant, good - bad, and beautiful - ugly. The second dimension, arousal, relates to variables concerned with quickness, warmth, excitement, agitation and such like, e.g., active - passive, but also fast - slow and hot - cold.

When looking at tangible and embodied interaction, the artefact as such (the appearance, the quality, the cultural associations etc.) can evoke certain emotions, the direct interaction with the artefact can evoke emotions, and also the context can trigger certain emotions, e.g., by bystanders. All these forms of emotions can be evoked when looking at the examples given in this book, ranging from artefacts that spark excitement, evoke quiet pleasantness when interacting, or even evoke melancholy or sadness. Tangible and embodied interaction can however also be based upon emotional skills, e.g. by using interactive artifacts that can measure emotions and respond accordingly, or by expressing emotions through its dynamic form. For example, Wensveen’s alarm clock aims at detecting the emotion of the user through the settings of the clock (see Figure 6.25 top), with the aim to auditively respond in an appropriate manner, for example being more adamant in the sound of the alarm when the stress level of a person increases, e.g. when wanting to catch a flight on time [Wensveen et al. 2002]. Or for example the Spiky Starfish from Young Suk Lee, a cigarette bag that expresses an unpleasant form and aims at evoking an unpleasant feeling when consuming unhealthy harmful items like cigarettes [Lee 2015] (see Figure 6.25 bottom).

Cognitive Skills

Cognitive skills are used in many different ways and allow people to know, think and act in the world. Depending on the underlying paradigmatic framing (e.g. cognitive sciences or philosophy) they are used in different ways and for different things spanning from being able to act in the world, to interpret and abstract information, to constitute concepts, to remember, to direct attention, to reflect etc. Cognitive skills thrive well with structure, procedures, categories and order [Stienstra 2016]. Chapter 4 dives into the specificity of cognition, so we won’t spend too much time on the underlying mechanisms.

From a design and aesthetic perspective, tangible and embodied interaction are especially useful when dealing with situations placing a heavy burden on our cognition. Distributed

Figure 6.25 Interactive artifacts can measure emotions and respond accordingly in an expressive way, for example with Alarm Clock [Wensveen et al. 2002] and Spiky Starfish [Lee 2015].

cognition can offload this burden to the tangible environment. In distributed cognition, both processing and representing information are distributed over the brain and the environment [Hutchins 1996]. In concrete terms, this means that people actively reason with the information in the environment, and not merely represent information in the world. Making a shopping list, doing a calculation on a piece of paper, or putting the keys next to the door in order not to forget them are all forms of distributed cognition. Within the realm of tangible and embodied interaction, we already showed quite a few examples in the section discussing hermeneutics and embodied cognition to interact with abstract, complex or difficult to grasp matter (see Figure 6.10). Another example is explored by Konkel et al. [2019], who research how tangibles and display-rich interfaces can be used to support co-located and distributed genomics collaboration, a process that is very complex, requiring a high level of cognitive skills and which can benefit from distributed cognition using TEI (see Figure 6.26).

Social Skills

Last, but certainly not least, people also rely on social skills to engage with others, to interact with them, to disagree with them, to cry and laugh together, and to learn from and with them. When Dourish [2001c] coined the term embodied interaction he referred to products, objects, conversations, actions etc. that unfold in a meaningful social as well as physical world. *"The ways in which we experience the world are through directly interacting with it, and that we act in the world by exploring the opportunities for action that it provides to us - whether through its physical configuration, or through socially constructed meanings. In other words, they share an understanding that you cannot separate the individual from the world in which that individual lives and acts."* [Dourish 2001c]. Also researchers like Suchman and De Jaegher stress the importance of social interaction and skills. With her Situated Cognition theory, [Suchman 2007] explains how people continuously coordinate their own actions in relation to the actions of others, while being embedded in a socio-

Figure 6.26 TEI supports co-located and distributed genomics as a way to deal with complexity [Konkel et al. 2019].

Figure 6.27 a) Scope, a photo camera to support the psycho-social development of children living in (former) warzones (photo Bas Groenendaal; b) Fida: a voice-recording device to communicate difficult messages without being present (photo Marcel Verbunt) [Hummels et al. 2008].

cultural situation. De Jaegher and Di Paolo [2007] coined the concept called participatory sensemaking, being a shared process of sensemaking amongst people, grounded in ongoing embodied and situated interactions. Section 6.2.5. showed already many examples of tangible and embodied interaction based upon people's social skills. Also when social interaction is difficult, tangible and embodied interaction can be used as a direct mediator to engage with others, like Scope or Fida anticipated, two designs by (former) Master's students Industrial Design to support youngsters interacting with the world (see Figure 6.27). Scope is a see-through photo camera which is used to stimulate the psycho-social development of children living in (former) warzones. Fida is developed for young children to communicate emotionally intense moments to their parents in an indirect way by leaving a voice recording [Hummels et al. 2008].

Concepts of the Body

Next to looking at the various skills of people, we can also open up the design space by looking at the body as a whole. Loke and Robertson [2011] discern six concepts of the body:

1. Body as anatomy and physiology, i.e., the organic body referring to e.g. our skeleton, our muscles, our respiratory system etc., which can be supported through tangible and embodied interaction, but which can also be measured and taken as a starting point for interaction.
2. Body as expression, connected to concepts such as creativity, evolving processes and transformation, where the body is continuously showing to others what we do and how we feel, e.g. e.g. a feeling of stress through our posture, fiddling with our fingers and a blush on our cheeks. Disciplines like dance build upon this capability of the body.
3. Body as knowledge, building upon the body as a thinking tool, supporting memory and connecting to history. People use their body to explore concepts, choreographies, or even do mathematics using their body [Rosenfeld 2017]
4. Body as physical skill, can often be seen in the TEI community, making use of the physicality, dexterity and physical experience people have to interact with the world, be it in a sport, gaming or health related setting, e.g. [Mueller et al. 2017], or just in the richness and subtleties of everyday interaction [Frens 2006]; [Djajadiningrat et al. 2002a]
5. Body as felt experience, related to concepts such as perception, emotions, sensory experiences and concepts such as kinaesthetic awareness where a person is self-aware of his body in motion. Tangible and embodied interactions used for sensing and extending the body, as described in section 6.2.1., are linked to this concept of the body.
6. Body as social, cultural, is closely related to the above described social skills of people. It relates to intersubjectivity and communication. Or as [Merleau-Ponty 1962] indicates, it relates to the body-for-others, i.e., it is within through the interaction with others that our actions acquire meaning.

In the next section, we see how these different forms of the body play a role in the dynamics of interaction, leading to various forms of aesthetics of interaction.

Designing Devices to Evoke Aesthetics of Interaction

Many books have been written about design and aesthetics, and we do not want to redo them here. At the start of this chapter we already introduced several different perspectives on aesthetics of interaction. In this section, we explain the practical consequences of the different approaches and directions for the device to be designed. Chapter 5 already looked at the available technology to develop artefacts. This section focuses on the main elements one can use for designing for the aesthetics of tangible and embodied interaction, with an emphasis on dynamics to reach aesthetics of interaction, which seem to be one of the core qualities of tangible and embodied interaction. This section explains briefly the static material qualities as well as the dynamic material qualities.

Properties of Artefacts

How to create the form of and interaction with artefacts so that they are understandable and usable? Formgiving is the discipline that focuses at the appearance of and interaction with artefacts, focusing on e.g. ergonomics, functionality and expression, including non-obvious information which allow users to perceive e.g. what the artefact is for, how it can be used, how sturdy it is, which emotions it targets at, what socioeconomic community is it designed for [Smets et al. 1994].

Formgiving is an important aspect when designing tangible and embodied interaction. Today, the world of human computer interaction (including TEI), and the world of industrial/interaction design are heavily interwoven, but that has not always been the case. After the fifties, when Modernism decreased and slowly but certainly faded out in the Western world, and unifying ideologies were disappearing, design was pushed to beautiful appearances "packaging", missing the electronic and digital boat [Overbeeke and Hummels 2013b]. The development of interaction with the “ungraspable” was divided between the Human Computer Interaction (HCI) community doing the engineering and interaction thinking, and the Industrial Design (ID) community beautify the new machines and interaction [Frens 2006; Overbeeke and Hummels 2013b]. The emphasis of the artefact and interfaces was placed on ’cognitive’ interaction with displays and dozens of neatly organised buttons. As a response, the post-modernist movement Il Nuovo Design, started promoting principles such as diversity, ornaments, colour and experience, and products like Swatch watches and Apple’s colourful iMac were heavily influenced by this movement [Horn 1985]. Over the years the worlds of HCI and ID integrated, leading also to emerging fields like Interaction Design. As can be seen in the TEI community, many different disciplines continuously collaborate nowadays.

When looking at the aesthetics of appearance and interaction, this collaboration of disciplines is necessary to integrate product behaviour, software code and the topic of this section product appearance [Baskinger and Gross 2010]. In section 6.5, we’ll elucidate several design principles related to form and dimensions.

Design elements like material and texture are also strong mechanisms within formgiving. We see various studies on materials surface within the TEI community. Only recently, Hayes and Hogan [2020] presented at TEI’20 the type of materials used for tangible and embodied interaction, as reported upon during the last 12 TEI conferences from 2008 till 2019. They pointed out that TEI developers have the highest preference for plastics, as well as a preference for metal, wood and paper. Maybe more surprisingly, 72% of the materials they identified where one-offs, only detected once in all the publications, although this could in many cases be explained due to the high costs of the material (e.g. silver), the specific technical functionality

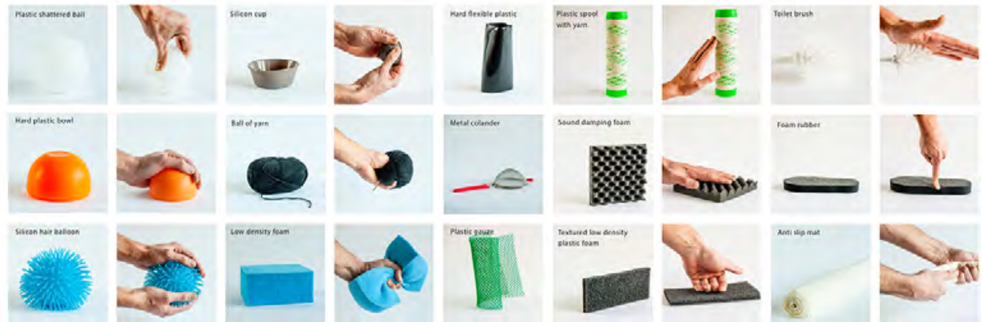

Figure 6.28 An exploration on how to tune in or out a feeling of melancholy using material qualities [Karana et al. 2016].

of the part (e.g. transparent adhesive film), or the specific role it had (e.g. hair). Their study did not focus on interactive materials, which would be the next step towards analysing materials involved and needed to support the dynamics of the interaction.

This inventory does not directly help in designing with materials when aiming for a certain aesthetics. The Materials Experience Vision by Karana et al. [2016] might be of more use. They discern four material-related characteristics that can help in shaping the targeted experience when interacting with an artefact: 1) *sensorial*, i.e., what the person is feeling, e.g. a soft and warm feeling, 2) *interpretative*, i.e., what the material is expressing, e.g. a natural, elegant and sober expression, 3) *affective*, i.e., which emotions or mood is the material evoking, e.g., triggering nostalgia, and 4) *performative*, i.e., which kind of actions is the material inviting, e.g., the material will require delicate use [Karana et al. 2016] (see Figure 6.28).

Dynamics of Interaction

One of the main advantages of tangible and embodied interactions in comparison with graphical user interfaces is its possibility to make extensive use of the bodily capacities of a person in space and time. Shaer and Hornecker's elaborate overview of tangible user interfaces indicated well over 10 year back, an upcoming research focus on whole-body interaction and performative tangible interaction: *"... with a traditional TUI users tend to only manipulate objects within arms' reach using their hands and arms. Emerging systems allow users to interact with large objects within a large space, requiring full-body movement."* [Shaer and Hornecker 2010b]

Hornecker and her colleagues were themselves inspired by Oskar Schlemmer's Triadic Ballet costumes from the 1920s, regarding whole-body interaction. Schlemmer, an artist from the Bauhaus movement, developed costumes to create new expressions and stress the beauty and possibilities of the movement of the human body (see Web Companion 6.1).

Figure 6.29 Interactive costume inspired by Oskar Schlemmer's Triadic Ballet costumes from the 1920s [Karpashevich et al. 2018].

Web companion 6.1 (design/figs/a1)

Hornecker and her colleagues were inspired by Oskar Schlemmer's Triadic Ballet costumes from the 1920s, regarding whole-body interaction. [a]

[a] https://en.wikipedia.org/wiki/Triadisches_Ballett

The new interactive wire costume from [Karpashevich et al. 2018] *"restricts lower body movements, and emphasizes arm movements spurring LED-light 'sparks' and 'waves' wired in a tutu-like costume"*, thus aiming to introduce different movements, feelings and moods.

During the last decade there are a multitude of artefacts developed based on whole-body interaction, as can also be seen in this book. Whole-body interaction, coined by [Hornecker and Buur 2006a] is also known as movement-based interaction, an area focusing on meaning, richness and subtleties of the movements in interaction, i.e. movements of and between the user and the product [Hummels et al. 2007].

Let's take a simple example of a coffee cup to explain the potential richness when focusing on the richness interaction and movement (even though this example is not an interactive product). *"Suppose I am alone in an outdoor cafe wanting to drink a cappuccino. The form and interaction possibilities of the cup that the waiter is bringing me, afford me to drink. And while drinking, I can hold it in a plethora of ways, thus enabling me to create my own expression. When he serves me a cappuccino and an espresso, both cups afford drinking in a completely different way. It is not merely the difference between the cups as such but, also, the coffee itself is changing my way of drinking, because it has e.g. a different temperature, texture, weight and amount. If I'm drinking the cappuccino during a different day, I will drink it in a different way, because the situation is different. I might feel differently, behave differently or have a different intention, e.g. I am in a hurry and want to quench my thirst or I want to enjoy the evening by drinking something together with my friends. Even drinking a cappuccino in the Netherlands or in Italy changes the experience, my behaviour and my movements. In a social setting, it can change the behaviour of others. They can read from my cup how long it takes me to finish it,*

Figure 6.30 A prosthetic tail [Nabeshima et al. 2019a,b].

so they will most likely not leave before I have finished my cup. In case they are in a hurry, they might urge me to drink more quickly which changes my behaviour and movements when interacting with the cup. And this is still in the context of an outdoor cafe. I can drink a coffee from the same cup at the beach, and its meaning will change for me. When I have finished my coffee, the cup affords me to build a sandcastle with my kids if desired. In both situations at the beach, compared to the outdoor cafe, I will most likely use and handle the cup in a different way."

It is the 'openness' of the design that enables the functionality to change, the interaction to change and the behaviour to change, all dependent on the situation. The aesthetics of interactions are not merely based on the possibilities and specifications of the cup in action, but also on the mood, bodily skills and intentions of the person drinking as well as the context, such as time, place and social setting. And this is just a simple cup. You can image what the implications could be for designing tangible and embodied interaction with dynamic products. When looking at the contributions within TEI we see different sources of inspiration to explore and design the aesthetics of dynamic interaction, e.g. nature, dance or the everyday life of people. Some of these approaches focus more on the qualities of the movement as such, whereas others focus more on the temporal and spatial aspects in relation of to the situation and context. In the following we'll show a few different examples.

Biomimicry

When looking at literature and developments in the TEI community, various researchers got inspiration from nature and biology to analyse and design the qualities of movement-based interaction, more specifically biomimicry. For example, Nebashima and colleagues developed Arque, a biomimicry-inspired anthropomorphic tail that expands the human bodily functions and can provide e.g. haptic feedback as a response to virtual forces [Nabeshima et al. 2019a,b] (see Figure 6.30).

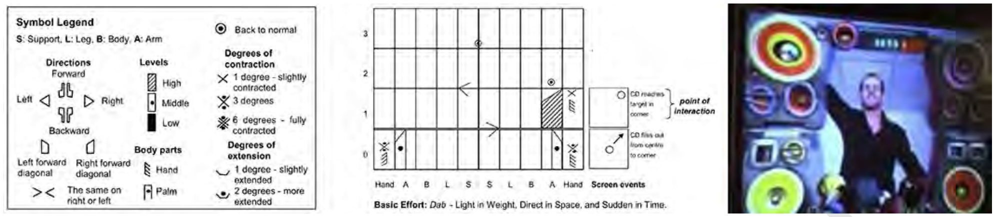

Figure 6.31 Legend of Labanotation and an example of a filled-in diagram for an action in the Beat Freak game [Loke et al. 2005]

Laban

One of the most renowned movement-related frameworks is the Laban movement analysis. Rudolf Laban developed in the 1920s his Labanotation, a framework used to record and analyse movements, which was further developed by Hutchinson and others at the Dance Notation Bureau in New York [Hutchinson 1977]. Laban's framework has been used in various disciplines including dance choreography, physical therapy, drama, anthropology, design, and tangible and embodied interaction, and offers a powerful way of both choreographing all kinds of human movements, as well as analysing these movements. Labanotation is based on different parameters [Bartenieff and Lewis 1980; Loke et al. 2005]:

- *"Motif"*: describes the key features of the movement
- *"Effort"*: relates to the expressive aspects of the movement and the attitude of the person moving, more specifically to the potential / energy of the movement. Effort is described in weight, space, time and flow.
- *"Shape"*: also relates to the expressive aspects of the movement and the attitude of the person moving, but in this case to the spatial shaping of form, described in terms like growing, shrinking or carving.
- *"Structural"*: describes the structural elements of the movement in full detail and measurable terms, e.g. the different body parts, the specificity of space regarding direction, distance, degree of motion etc., time aspects such as duration, as well as the quality of the dynamics.

Within the world of tangible and embodied interaction various researchers used Labanotation to analyse interactions, such as [Loke et al. 2005] (see Figure 6.31).

Moving and Making Strange methodology

Many researchers have used these movement qualities and translated them into methods to design and choreograph with, as Loke and Robertson [2013] show in their paper, including their own Moving and Making Strange methodology (see Figure 6.32). This methodology of-

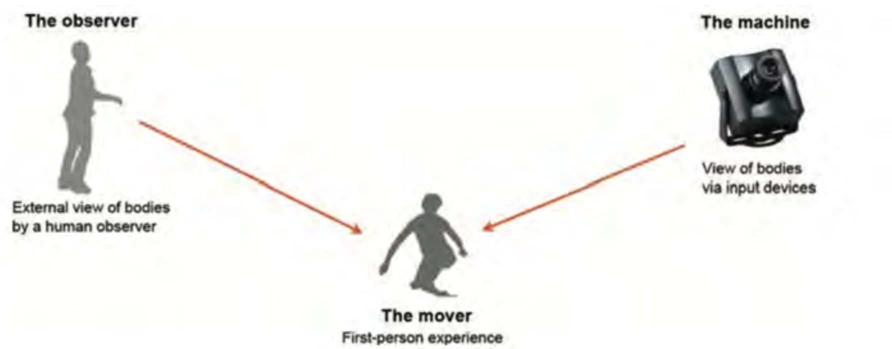

Figure 6.32 The Moving and Making Strange methodology makes use of three perspectives: the mover, observer and machine [Loke and Robertson 2013]

fers designers a set of principles, perspectives, methods, and tools for exploring and testing movement-related design concepts starting from the principle of estrangement. *"The notion of "making the familiar strange" is described in relation to the moving body by the phenomenologist [Sheets-Johnstone 1999]. Through varying our normal movement patterns and processes we can unsettle our habitual perceptions of the world and ourselves. One way of reacquainting ourselves with familiar or habitual movements is to do a familiar movement differently, to perform the movement with a range of kinetic variations and so reveal the specific felt quality of the original movement"*. Loke and Robertson's [2013] methodology is structured around the three perspectives: the mover, observer, and machine, and offers a list of key activities to progress.

- Investigating movement
- Inventing and choreographing movement
- Re-enacting movement
- Describing and documenting movement
- Visual analysis and representation of moving bodies
- Exploring and mapping human-machine interaction
- Representing machine input and interpretation of moving bodies

Choreography of Interaction

A closely related methodology is Choreography of Interaction developed by Klooster and Overbeeke [2005] (see Figure 6.33 left). This design framework is based on the trinity of physical involvement, expressed meaning and dynamic qualities, more specifically, it sees

Figure 6.33 Choreography of Interaction framework developed by Klooster [2005] which was applied in various design including a flower arrangement and a greeting ritual. (photo courtesy Sietske Klooster)

movement as the embodiment of interaction. The framework facilitates the exploration of the relationship between product form, movement and semantics for interaction design. For example, when designing a new vase, the flower arrangement was the starting point for developing the choreography by Klooster, and the final vase was the embodiment of this choreography, inviting the user to focus on the arrangement of flowers too (see Figure 6.33 middle). Bachelor students of Industrial Design, TU/e learned and used the framework in their project to design an interactive greeting ritual, starting from various ways of moving and greeting, thus developing a device to facilitate the choreography of greeting (see Figure 6.33 right).

Everyday rituals

Instead of coming from the specifics of (the choreography of) the movement, dynamics can also been approached from a wider spatial and temporal perspective, i.e., the perspective of an everyday ritual. The situatedness of everyday experiences results from the multiplicity of considerations of artefactual, social, spatial, symbolic, performative… elements. The complex spatial and temporal arrangement of these elements structure the experience. The design for everyday rituals focuses on creating such an arrangement in a way that not only the outcome, but also the experience itself is harmonious, so that it creates meaning in the experience itself. Such design distinguishes itself from a more classic design aiming at a certain result (e.g., a coffeemaker making a good coffee) by integrating in the design consideration the way the result can be beautifully obtained (e.g., a nice way of making a good coffee).

The temporality extends therefore to a larger scope, which also invites the designer to consider the aesthetics of three different levels: the aesthetics of each element (artefacts, places, gestures, etc.) involved in the experience (structural level); the aesthetics of the relationships

Figure 6.34 3D printed artefacts for the Japanese Tea Ceremony based on the aesthetics of irregularity. (photo courtesy Pierre Lévy and Shigeru Yamada.)

between these various elements (interactive level); and the aesthetics of the harmony of the experience as a whole in the way it unfolds over time (experiential level) [Lévy 2018b].

For example, during his master graduation project, Shigeru Yamada has worked on the aesthetics of imperfection and irregularity, designing artefacts for the Japanese Tea Ceremony [Lévy and Yamada 2017; Yamada 2016] (see Figure 6.34). The design challenge was twofold:

- revisiting the notion of imperfection [Yanagi 1989] using new production techniques (3D-modeling and 3D-printing), leaving the complete agency of creating imperfection to the 3D-printer. To do so, the designer changed the printing speed, so that the 3D-printer would not be able to produce the artefacts in a "perfect” way, but rather create unplannable imperfection, considered as beautiful irregularities.
- involving technology in the ceremony itself. First the utensils produced by the new production techniques were used in a night tea ceremony (yobanashi), during which candles are usually used to make light in the tearoom. Instead a discreet intelligent light system was mounted in the tearoom, controlled by a Kinect, so light would beautifully behave according to the progress of the ceremony.

In the continuation of this work, Lévy [2018a] focused on the designing of every experiences. Based on an auto-ethnographical-like approach to making hot chocolate in a morning ritual (see Figure 6.35), he pointed out the complexity of designing with the aesthetics of the harmony in mind, and pointed out various aspects to consider:

- *Place and time*: the coincidence of space and time (a ritual takes place at certain times in certain places) triggers the attention required for the ritual to be fully experienced as such.
- *Essentiality of elements*: the elements involved in the experience can be either essential or contingent. Some elements, because of their functional nature (e.g., a cup to contain the hot chocolate) or their relational nature (e.g., the bowl with which I have learnt to make a “proper” tea) may be necessary for the ritual to experientially take place. Some other elements may be missing while the ritual can still be performed.

Figure 6.35 The making of hot chocolate in a morning ritual (photo courtesy Pierre Lévy)

- *Strength of elements*: often details of designs make a ritual more enjoyable (or simply more beautiful) than without such detail (e.g., the quality of the coffee grind).

Design Principles

As we explained in section 6.1., evoking a sense of beauty and affect during interaction can be done in various ways, e.g. using a semantic approach or a direct approach [Djajadiningrat et al. 2002a; Fishkin 2004]. Both approaches are based on different paradigms. Semantics is related to the cognitive science paradigm. This paradigm regards interaction as information processing, where the information in an artefact is processed in the user's brain using his long-term and working memory [car]. Based on the user's goals and his subsequent intention to act, he executes a number of actions, which the user perceives, interprets and evaluates in comparison with his goals [Norman 1988b]. The direct approach is based on a paradigm that starts from being in the world [Merleau-Ponty 1962], where perception is not a passive act but actively used to create meaning in interaction. As we could see in various examples in this book, the approaches are often combined, e.g. as Klooster and Overbeeke [2005] show and explain in the Choreography of Interaction approach (see Figure 6.33).

Different paradigms, starting points and originating disciplines ask for different ways of designing and consider different design principles valuable to create valuable aesthetic designs. In the previous chapters, we showed already various frameworks and approaches to support designing tangible and embodied interaction. For example, [?] propose image schemas and metaphorical mappings as a framework for analyzing and designing tangible interfaces, as discussed in chapter 4. Chapter 3 shows at the end an overview of many frameworks available to support abstracting, designing and building tangible and embodied interaction. In this section, we will elucidate three sets of design principles with concrete examples to support the design process and obtain aesthetic interaction. These three approaches do not attempt to be all encompassing, they merely try to provide inspiration.

CRAP

The CRAP heuristic, **C**ontrast, **R**epetition, **A**lignment, and **P**roximity, is well known in visual and user interface design circles. The heuristic has relevance not only to the *visual* appearance of tangibles, but also to their *material* composition. Toward this, we briefly consider these in a TEI context. Longer elaborations of CRAP are available in print and online, e.g. Greenberg [2007]; Renew [2016]; Reynolds [2008]

- **contrast:** One definition of contrast is "opposition or juxtaposition of different forms, lines, or colors in a work of art to intensify each element's properties and produce a more dynamic expressiveness" [Dictionary]. This speaks to both aesthetic facets, basic legibility, as well as to the intentional effort to manage attention. For TEI, contrast has both visual dimensions: light and dark, wide and narrow, color amidst gray. Contrast in physical materials is also an important consideration: e.g., wood against metal, leather, fabric, stone, or glass. With contrast, neither *more* or *less* is inherently "better." Excessive use of contrast can create competition for attention, potentially to disorienting effect. In some contexts – e.g., in attempts to engage visceral emotion – this can be desired; more often, it is not. Similarly, too little engagement of contrast can easily detract from legibility, or insufficiently engage the attention of the target audience. Many issues of basic functionality also lie within. If a user cannot distinguish (e.g.) a functional from a non-functional element (e.g., a button, RFID/NFC sensing zone, etc.), it is difficult for her to engage. (Again, in some cases, this may be desirable, as with hidden or infrequently used elements). Although in CRAP contrast is generally related to visual contrast, the principle applies to all sensori-motor skills. When looking at developments like shape-changing interfaces, aspects such as contrast become crucial to detect subtle differences in shape. Especially given that the design of such interfaces is still in its infancy, exploratory investigations towards a basic form language to obtain such subtleties can contribute to the field. For example, Winther and Vallgårda [2016] explore these aesthetics subtleties, including elements such as contrast (see Figure 6.36).
- **repetition:** In the early days of desktop publishing and word processors, a common design "mistake" was the use of many different (and often disharmonious) fonts, colors, and/or layouts. The repetition element has a number of aspects. Visually, repetition can suggest use of a relatively few fonts; common heights or widths of images; etc. Physically, repetition can relate to consistency and reuse of physical interactors (knobs, tokens, etc.). Functionally, repetition also speaks to the computationally-mediated behavior of interactive elements – e.g., maintaining expectations of behavior in response to similar gestures or engagement with similar artifacts. Moreover, as the previous example in Figure 6.36 shows, repetitions can also be used as expressive and function power in more dynamics interaction, as also TRANSFORM, InFORM ((see Figure 1.16) and many of

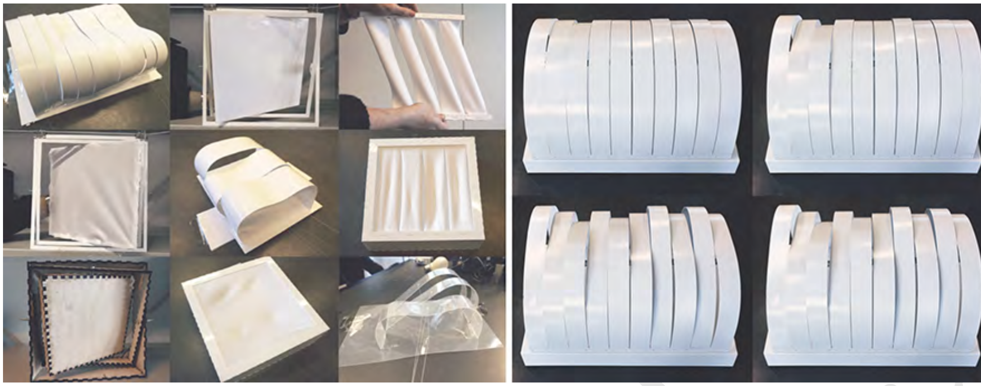

Figure 6.36 Various shape-changing interfaces exploring aspects such as contrast [Winther and Vallgårda 2016]

the other shape-changing interfaces developed by Hiroshi Ishii's team reveal [Ishii et al. 2015b].

- **alignment:** Alignment concerns the relative placement of elements within a design, toward the creation of order and the fostering (per an upcoming term of extended interest) legibility. The position of each tangible exists in relative context with sister tangibles. Whether mechanically fixtured (to the work space or each other), or in evolving physical context of a game-board or other work surface, alignment stands as a key principle of visual and physical structure. The earlier shown design called Foxels (see Figure 6.9) even uses the principle of alignment as its basic starting point. This smart, modular furniture allows owners to build and customize their own interactive furniture, by arranging building blocks in a clear grid [Perteneder et al. 2020].
- **proximity:** Finally, also proximity is often used as a central ordering principle underlying tangibles. While they are first expressed in a technology context (and operationalized e.g. in proximity sensors), this is equally true from the perspective of the visual and physical design of a TEI system. Whether computational mediation is integral, proximal, or distal to one or several tangibles – and the particulars of how this integration or proximal juxtaposition is achieved – are central to the creation of TEI systems. When looking at peripheral interaction as the examples given in section 6.2.3., proximity gets a different connotation, where tangibles cannot only be spatially proximal or distal, but also experienceably being in the proximity of one's attention or not (see Figure 6.14).

Figure 6.37 The two objects on the right aim to express 'inaccessible' and 'few', where the left one aims to express 'light' and the right one 'heavy'. The two objects on the right aim to express 'accessible' and 'few', where the left one aims to express 'old' and the right one 'new' [Djajadiningrat et al. 2002a]

LAVA

The LAVA heuristics, which look beyond the characteristics of solely form and interaction – **L**egible, **A**ctionable, **V**eritable, and **A**spirational – provide another conceptual tool for regarding representation and control within interaction design in general and tangible interfaces in particular [Ullmer 2012a; Ullmer et al. 2016b]. In this section we briefly describe the four elements. A more elaborate description of LAVA can be found in the appendix. Moreover, information about the Enodia tangibles, which are designed based on the LAVA principles, can be found in chapter 1, 5 and the Appendix.

- **Legible:** Are tangibles expressed in physical and visual representational forms that allow users to "read" them? In most rudimentary form, TEI legibility engages the question "what does a given tangible mean?" Legibility has many facets. For example, in contemplating Bishop's marbles answering machine, a given marble could potentially be associated with almost anything – be that digital (e.g., virtual content referenced via a web address), physical (e.g., a person, place, or thing), or conceptual (e.g., different ideas or challenges). Legibility can be obtained in various ways, through form, colour, contrast, cultural connotation, etc. Legibility can be obtained using semantics and semiotics building upon culturally embedded connotations and meaning, as well as through as "direct" approach which takes behaviour and action as its starting point. For example, Industrial Design students participating in a Formtheory course, explored expressive dimensions through making hand-sized sculptures which were expressive on different dimensions, exploring dimensions such as quantity, accessibility, weight and age [Djajadiningrat et al. 2002a] (see Figure 6.37).
- **Actionable:** Most of the TEI systems we have discussed engage computationally-mediated interaction: touching something, moving something, throwing something – in short, doing something. Talking about legibility, one can also ask how one can see and be invited to perform an action? What makes an artefact actionable and how to de-

sign for this? The previous examples expressing (in)accessibility and weight on those two dimensions, but there are many more aspects that determine if an artefact is actionable. In section 6.1.1. we already introduced the direct approach and the concept of affordances. The Interaction Frogger Framework supports designers to get grip on actionability, through designing and specifying functional, inherent and augmented feedforward and feedback [Stienstra et al. 2012; Wensveen et al. 2004b]. The framework includes six dimensions to create feedforward and feedback: time, location, direction, modality, dynamics and expression. Wensveen's alarm clock that was show in Figure 6.25 was developed using the Frogger Framework.

- **Veritable:** Do tangibles and the interaction with them provide means to ascertain the accuracy of represented content, and their interpretations thereof? For example, how accurate is the Pinwheels of Dahley, Wisneski, and Ishii [1998a; 2001b], where the spinning of pinwheels was ascribed to the changing stock market values (see Figure 6.14). Before the day trader acts on such stimuli, one might do well to ask: am I sure what I think is represented corresponds with "reality"? And what happens if the purpose of an artefact is to confuse or distort the connection with reality, e.g. as evoked in the co-op game Human and Dog [Hou et al. 2017a]?
- **Aspirational:** Do tangibles provide aesthetic motivation to engage, and suggest paths toward creating forms? Not all tangibles are equal in their potential to invite (or demand) engagement. Just as the potentials between an ill-conceived and executed art book, sculpture, or building differ profoundly from their aspirationally realized kin, the same is at least equally true for tangibles. This is not to equate "professionally-executed" or "expensive" as the inevitable target of tangibles. For a parent or grandparent, a young child's accomplishments with clay or popsicle sticks may well be an evocative, highly aspirational artifact – and, aspirationally for us, even a heavily mediated tangible. But it is to say that mileage and execution varies widely, as well as matter. There is a relationship between the terms "aspirational" and "inspirational." For several years, both terms were included using the abbreviating LAVIA. However, there was a challenge clearly differentiating the two, and the uncertainty whether inclusion of both terms was more compelling for conceptual engagement than one alone. Wendy Mackay (Inria) indicated that "inspirational" might be regarded as a "pushing" force, with "aspirational" as more a "pulling" force. To embrace the "pulling" force, Ullmer et al. [2016b] settled for some years on the LAVA variation.

The aesthetics of the impossible

During his inaugural lecture, Kees Overbeeke (1952-2011) introduced the concept *Aesthetics of the Impossible* based on his design principles or better, his beliefs, since he was convinced that beliefs can guide people what to do, where to go and look, and what strikes our eyes

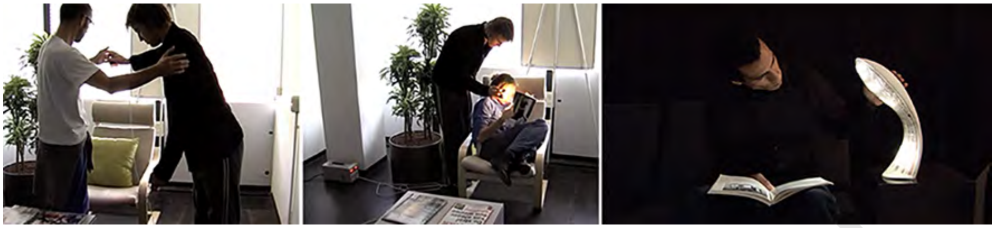

Figure 6.38 Dancers acting out intelligent lamps, aiming to elicit value related behaviours from participants. The dancers' interactions are studied to find guidelines for the final AEI lamp design[Ross 2008]

[Overbeeke 2007]. Being grounded in embodied theories like the ecological theory of perception [Gibson 1979b] and phenomenology [Merleau-Ponty 1962], and embracing the notion of creating meaning in interaction, he considered it important to start from design beliefs that inspire designers, instead of offering 'absolute' general design principles that can be applied always and everywhere. His beliefs where slightly adjusted in the chapter *Industrial Design* in the The Encyclopedia of Human-Computer Interaction, 2nd Ed. [Overbeeke and Hummels 2013b], which turned out to his last publication. In this section, we briefly introduce his beliefs/principles and illustrate them with some examples from tangible and embodied interaction. For more information and theoretical embedded, we advise to read the chapter *Industrial Design*.

- **Being in the world**

  Design is about people. It is about our lives, our hopes and dreams, our loneliness and joy, our sense of beauty and justice, about the social and the good. It is about being in the world.

  As shown in section 6.2., artefacts are not merely a means to execute a function; they mediate our relationship with the world, with all its complexity and subtleties. They are not neutral and can resonate with our emotions, our dreams, our values. Based on *Being in the world* theories and principles, Philip Ross developed during his PhD the intelligent lamp AEI (short for Aesthetics and Ethics in Interaction), as a research vehicle to explore how design can affect a person's value level (see Figure 6.38). AEI has three sets of behaviour depending on the way the user stokes the lamp, which all three target at evoking a different value from the user during interaction: feeling helpful, having social power and experiencing creativity.

- **The primacy of action**

In accordance with Merleau-Ponty's, Dourish's and others' approaches to epistemology, we strongly believe that meaning cannot be detached from action. Meaning is in (inter)action. There is a primacy of embodiment.

Tangible and embodied interaction are based on the same foundation, so nothing new for the readers of this book. One can only question oneself during the design process, how open a design can be in order to facilitate the creation of meaningful interaction. In section 6.2., we introduced the example of the Augmented Speed-skate Experience [Stienstra et al. 2011] as the ultimate example of meaning-creating in interaction, where 'meaning-free' white noise was turned into meaningful bodily information by the skaters during action, which supported them to improve their posture and movements (see Figure 6.2).

- **Reflection on action**

A design theory must be a theory of action and the embodied in the first place, and of meaning in the second, and not the other way round. Reflection on action is the source of knowledge.

The primacy of action implies that cognition follows perception through action, including reflection. Schön [1983] as well as Dewey [1938] stress the importance of reflecting to let insights and understanding emerge from experience. Reflection in and on action is a powerful mechanism to learn and expand one's knowledge in and through action and doing, by entering into an experience without judgement and being surprised by one's reflections, thus opening up for learning from our actions [Schön 1983]. This principle invites the TEI developers to think through their hands, to develop prototypes early on, make their ideas experienceable, in order to reflect both in action during the making process, as well as after iterations to reflect e.g. with the users and stakeholders on the actions taken. The Studios, Workshops, Demos and Arts Exhibition during the TEI conferences embrace this notion of reflection in and on action together, and are highly adequate places for learning through doing (see Figure 6.39).

- **First / third person perspective**

The designerly way of looking is rooted in a 1st person perspective while intermittently taking a 3rd person perspective. Consequently, design relies on connecting the sensorial, intuitive to the abstract, analytical.

The interweaving of different points of view, including a first, second and third person perspective, forms an essential part of phenomenology, where one's own point of view can never be excluded. There have been various studies at the cross-section of theory and practice that explore the relationship between these different perspectives and switching between. In 6.2.1. we already elucidated the mechanical tail from Svanaes and Solheim [2016] (see Figure 6.6) as a means to explore the boundaries of a first person perspective

Figure 6.39 The strength of reflection in and on action and learning through doing is beautifully demonstrated at the various conferences at TEI. From left to right: a Studio at TEI'14, Demos at TEI'16 and TEI'17, and the Arts Exhibition at TEI'20. (photo courtesy Caroline Hummels.)

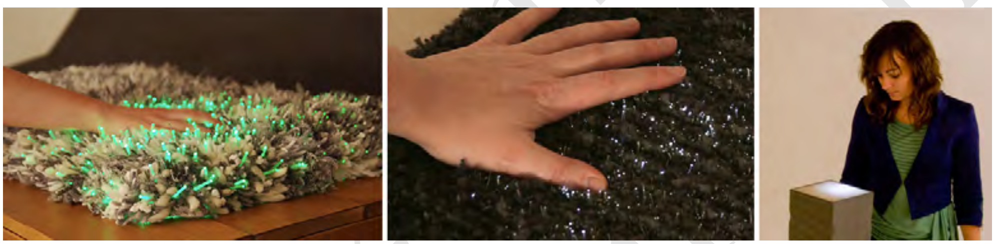

Figure 6.40 Perception Rug PeR (left), PeR+ (middle) and Perception Pillar PeP (right) (photo courtesy Eva Deckers)

and sensing oneself, thus feeding also his theory on the relations between the different perspectives [Svanæs 2013]. Smeenk [2016] explores the relationships between the three perspectives and the consequences for design, emphasising the role of the 2nd person perspective to bring empathy into the design process. Deckers [2013] investigates using a research-through design approach, how to experimentally test the switch between the first and third person perspective, based upon the notions from phenomenology. Through her intelligent installations PeR, PeR+ and PeP (see Figure 6.40), she explored the reciprocal interplay between the perceiver and the perceived, showing that this interplay positively influences the user's feeling of involvement during interaction with and intelligent artefact.

- **Creating opportunities for transformation through subtlety**

  Design can allow for transformation. It is about creating opportunities instead of solving problems. To do so, designers use ambiguity, uncertainty, open-endedness, and resistance. They take risks and dare to fail.

Figure 6.41 Beehugged is a concept developed to evoke people to act according the Universal Declaration of Human Rights, by exchanging power (electricity) through direct physical contact (left; photo courtesy Caroline Hummels) [Hummels and Lévy 2013; Trotto 2011]; and the Rotation project from Peeters [2017] explores the power of aesthetic engagement (right; photo courtesy Jeroen Peeters))

Transformation is a big concept and not easily reached. It is not only about the design as such and the values it might evoke, but also about a shift in attitude of the design team as well as of the "user". Together they can spark new behaviour to move towards a transformation. In her thesis *Rights through Making – Skills for pervasive ethics*, Ambra Trotto [2011] explored how design can evoke people to act according the Universal Declaration of Human Rights. For example, with Beehugged people can get power and recharge their mobile phone by hugging someone else [Hummels and Lévy 2013; Trotto 2011] (see Figure 6.41 left). And Jeroen Peeters [2017] explores in his PhD thesis how to design for aesthetic engagement, using skillful coping, intuition and reflection. He developed a multitude of prototypes to explore rich, open-ended and ambiguous ways of interaction, including the ones in the Rotation project: handheld objects without a practical function, so that it may only be interacted with for its own sake (see Figure 6.41 right).

- **Design methods**

The methods used must be rooted in design practice, in the socio-cultural and multi-cultural environment, invigorated by experimental and technological methods from other disciplines.

TEI is par excellence a multidisciplinary community (or even trans-disciplinary?), embracing the different perspectives, stakes, expertise, skills and contexts. One of the reasons for writing this book was the felt necessity to learn from each other, to share our knowledge and skills, and be inspired by each other's attitude. That also includes sharing and co-developing methods to develop tangible and embodied interactions. Methods for ideation and conceptualisation, methods for engineering, for evaluation and assessment, for debate and philosophical exchange, etc. But that also implies that we should not re-invent the wheel every time, e.g. by developing continuously new methods. We should go beyond the metaphor of toothbrushes regarding methods, as it was coined by John Zimmerman, i.e., something we all have but never share. It is about finding a shared language in doing.

- **Interweaving practice and research**

  Design practice and design research are powerful generators of knowledge. They are a way of looking at the world and transforming it. Consequently, design teaching and research should be interwoven.

  This TEI book aims at a diverse audience, from students wanting to learn the ins and out by applying the ideas, to companies exploring and sharing the value of TEI for their business, to researchers from the various fields to connect their expertise and learn from each other through collaboration. The connection between practice and research as an approach within TEI seems naturally incorporated within the DNA of the community, based on the principles of reflection on action as we explained above. Next to this, Chapter 2 shows many examples of TEI in the wild, commercialized through industry, or made robust through research, showing the potential of joining the different perspectives on practice and research. However, we should keep on pushing and exploring the connection between research and practice, due to what Bill Buxton [2008] calls *the Long Nose of Innovation... What the Long Nose tells us is that any technology that is going to have significant impact in the next 10 years is already at least 10 years old. Any technology that is going to have significant impact in the next 5 years is already at least 15 years old, and likely still below the radar. Hence, beware of anyone arguing for some "new" idea that is "going to" take off in the next 5 years, unless they can trace its history back for 15.* In order to see the many innovative ideas within the TEI community land as (commercial) common practice will require resilience and stamina.

- **Intuition and common sense**

  Intuition and common sense should be high on the agenda and exploited to the maximum. *Le sens commun n'est pas si commun,* as Voltaire said.

  Intuition has a weird status, where on the one hand everyone uses it in their everyday life, but on the other hand it is usually not considered as an 'official' modus operandi in the academic world, at least in the Western society. However, intuition is shown to be more suited for dealing with complexity than conscious thought [Dijksterhuis and Nordgren 2006], and developing tangible and embodied interaction can be considered to be a highly complex activity [Anderson and Krathwohl 2001]. *"Intuition begins with the sense that what is not yet could be … an imaginative experience ... that guides us towards what we sense is an unknown reality latent with possibility"* [**?**]. The TEI community can learn from each other with respect to intuition, especially from disciplines like art and design who are being more trained in applying intuition in their practices and more comfortable with ambiguity and uncertainty than some other disciplines. Transdisciplinary processes involving various disciplines, are beneficial to stimulate intuition and common sense.

Summary

In this chapter, we focused on the act of designing tangible and embodied interaction, more specifically the aesthetics of TEI. We showed through classifications of potential human-technology-world relationships how to realise aesthetics in interaction, thereby addressing its scope, the person's abilities, values, skills and needs, as well as the richness of the artefact including its form, materials and dynamics qualities. We showed many examples to elucidate how to create meaningful interactions and how the richness and subtleties of materials and dynamics can fit the skills and modalities of a person.

In the next chapter, we dive into the evaluation of TEI, showing various ways this can be done.

7 Evaluating TEI

In previous chapters, we reviewed the theoretical foundations of TEI, as well as the technological and aesthetic aspects of TEI design. Chapter 2 also discussed how TEI can have real world impacts by surveying example interfaces that have been deployed "in the wild" in areas of learning, social connectedness, and health and wellbeing. In doing this, we touched on the broad topic of evaluating TEI systems. This is a topic that merits further discussion, and this chapter thus provides an overview of some of the different ways that TEI systems and applications can be evaluated, not only "in the wild", but also in a lab setting.

The question of evaluation is an important one for the TEI community, which is inherently interdisciplinary in nature. The theory and practice of TEI by necessity brings together viewpoints and practices from various science, technology and engineering fields, as well as from art and design disciplines. As such, TEI researchers and designers need to consider what evaluation method (or mix of methods) will work best on a case-by-case basis, depending on the specific goals of a given project. The diversity of disciplinary viewpoints in TEI can inspire designers to consider different perspectives on the evaluation of TEI systems. Rather than providing a comprehensive list of evaluation methods used in TEI, we thus describe evaluation strategies through a series of examples that are organized into five different perspectives: user interaction, cognition, technology, arts, and philosophy. Note that these perspectives are not intended to be mutually exclusive, and researchers and designers may take on multiple lenses to consider the evaluation of their designs.

User Interaction Perspective

A central aspect of TEI design is that it introduces new techniques for interacting with computational systems. From a user interaction perspective, TEI designers might ask how successful a TEI system is (or how successful specific interaction techniques within a TEI system are) with respect to various criteria. For example: How easy is the system to use? How understandable are the interactions? How well does the system support the given tasks? How enjoyable is the system to use? How engaging is the system? These and other related questions are typically evaluated using methods from HCI, either as empirical lab studies or as in the wild field studies. Also, given that TEI systems often introduce novel interaction techniques that serve as a contrast to the dominant GUI paradigm, many studies have taken a comparative approach in order to investigate the costs and benefits of different interaction styles [Shaer and Hornecker 2010b]. Tests of usability, performance and usefulness are common, and employ measures such as task completion time and error rate, as well as user satisfaction and subjective

Figure 7.1 FlowBlocks [Zuckerman et al. 2005] is a TUI-based modeling and simulation environment consisting of wooden blocks with embedded computation that are connected to create models of data flow structures.

task workload, as captured with assessment tools such as the System Usability Scale (SUS) [Brooke 1996] and the NASA Task Load Index (NASA-TLX) [Hart and Staveland 1988], among others. Qualitative approaches, such as ethnographic observation, interviews, and the interaction analysis of video-recordings, are also frequently used in TEI user studies, and help to paint an overall picture of how users interact with and experience a given system. In some cases, TEI studies also investigate the hedonic qualities of the interactive experience, such as aesthetics and enjoyment.

To illustrate TEI evaluation from a user interaction perspective, we describe two example studies that cover a number of the approaches and instruments described above: a lab-based comparative study of TUI and GUI versions of the FlowBlocks modeling and simulation system [Zuckerman and Gal-Oz 2013] and an in-the-wild study of the usability and learning impacts of the Teegi educational support puppet [Fleck et al. 2018]. Our focus here is not on the design of these systems or on the specific study results; rather, we aim to highlight the evaluation methods used in each case.

FlowBlocks [Zuckerman and Gal-Oz 2013] is a TUI-based modeling and simulation environment consisting of wooden blocks with embedded computation that can be connected to create models of data flow structures (see Figure 7.1). The flow of data through the blocks is then simulated by lights that move from one block to the next at different rates and with different dynamic behaviors. In order to study the user interaction aspects of the system, the researchers developed a GUI-based version of the FlowBlocks system that used graphical blocks and mouse interaction, and then conducted a lab-based comparative study with 58 undergraduate students to evaluate the advantages and disadvantages of each interface with respect to user performance and preference. The study employed a counter-balanced within-subjects design, in which participants were first introduced to one version of the system and given 30 minutes to create and explain as many models as they could. After completing a questionnaire, they

Figure 7.2 Left: Teegi [Fleck et al. 2018] is a physical puppet that lights up to display areas of brain activity as children interact with its limbs and eyes. Middle/Right: children interact with Teegi during a user study that took place as part of a science workshop [Fleck et al. 2018].

were then introduced to the second version of the system and given 5 minutes to re-create the most complex model they had built with the previous version.

The interaction sessions were filmed and coded, and a number of criteria were used to evaluate performance, including the time required to complete a model, the number of blocks used, the number of types of blocks used, the number of times the model was touched, the number of connection errors, and the model type and correctness. User preference was evaluated using a combination of a post-task questionnaire and interview that assessed usability, intrinsic motivation, and flow. As is common in TEI studies, the researchers adopted questions from a number of different instruments for this purpose, including the System Usability Scale (SUS) [Brooke 1996], the Intrinsic Motivation Inventory [McAuley et al. 1989], and the User Engagement Scale [O'Brien 2010], as well as items adapted from Webster et al.'s [1993] flow scale. Lastly, a 10-minute semi-structured interview allowed participants to describe their interaction experience in their own words. They were asked about the advantages and disadvantages of each version of the system, which version they preferred, and their overall impression about the system. Thematic analysis was conducted on the interview transcripts in order to uncover emergent themes.

Teegi [Fleck et al. 2018] is a physical puppet that serves as an educational support to teach children about the relationship between brain activity and bodily functions. Areas of the brain that are involved in vision and in motor control of the hands and feet are displayed on Teegi when the puppet is manipulated (see Figure 7.2). For example, by closing Teegi's eyes or moving its limbs, different areas of its head light up to represent the corresponding brain activity. In order to evaluate the pedagogical potential of Teegi, the researchers conducted a mixed-methods user study with 29 schoolchildren (aged 7-11) in a real-life educational context. The study was part of a half-day school outing to a facility that develops educational tools and offers educational programs for youth. During the outing, students participated in a series of three 30-minute workshops that were designed to fit into the French STEM curriculum. In one of the workshops, Teegi was used by groups of 3-6 children at a time. The children were given 5 minutes to explore Teegi with an experimenter's help, followed by 10-12 minutes of unguided exploration. They completed questionnaires immediately after the interaction. The children were also given a pre-test and a post-test to assess their understanding of the brain. The pre-test took place one week before the workshop, while the post-test took place at least two hours after the workshop.

The study looked at the usability, desirability, and impact on learning of the Teegi interface. To do this, the researchers made use of a number of different instruments that focused not only on usability, but also on the hedonic qualities of the interaction experience. Rapid desirability testing [Hawley 2010] was used to orally gather the children's perceptions of the aesthetics, physical characteristics and visual qualities of the system; a short version of the Attrakdiff questionnaire [Lallemand et al. 2015] was used to assess both usability and attractiveness of the interface; and an extrinsic motivation test [Viau 1999] was used to assess the motivational value of the learning activity. During their interaction with Teegi, the children filled in observation sheets, which allowed researchers to study the nature of their observations, as well as to understand whether they had correctly identified the parts of the system. Additionally, the interaction sessions were videotaped and coded based on based on a behavioral assessment grid that looked at the children's interactions with the interface (moving, touching, etc.), activities (observing, inquiring, playing, etc.), and involvement in the interaction (number and duration of manipulations, expression of emotions, etc.). Lastly, the children were asked to depict their understanding of the brain in a pre- and post-test. This was used to assess conceptual change and impact on learning, which relates to the cognitive perspective discussed next.

Dr. Amanda Strawhacker, Tufts University
Evaluating CRISPEE as a Learning Tool for Young Children

The CRISPEE tangible toolkit allows children to create a genetic program that codes for a firefly's bioluminescent light (© author's personal photos).

CRISPEE is a tangible, developmental-appropriate tool designed to introduce young children (ages 5-8 years) to foundational concepts from bioengineering. The kit was developed by Prof. Orit Shaer and post-bac student Clarissa Verish from Wellesley College, and Prof. Marina Bers and Ph.D. student Amanda Strawhacker from Tufts University. CRISPEE is modeled on real-world bioengineering concepts, like the CRISPR/Cas-9 gene editing system, and tools, like DNA incubator/extractors. The tool allows children to play with genetic instructions as a coding language, in order to understand how gene editing can help to solve human problems.

The researchers who designed CRISPEE used design research methods to iteratively test and refine the tool and its implementation. Design research allowed for design changes to the prototype that were rooted directly in the effectiveness of the tool to support our educational goals. Specifically, CRISPEE was designed to introduce basic concepts of genetics and bioengineering, using the metaphor of coding with genes, and also to introduce children to the creative engineering design process and the ethical consequences of design choices. It was tested in two different naturalistic learning settings, the Boston Children's Museum and the Eliot-Pearson Children's School [Strawhacker et al. 2020a,b].

At the museum, over 60 children played with CRISPEE in brief 10 minute play sessions, and researchers observed their talk and tangible interactions with the tool. This study showed that children working alone or in pairs with CRISPEE came up with diverse ideas about how to use the blocks to create a new gene program, but 50% of children working in pairs and 63% children working alone mastered the tangible interactions after just 10 minutes of play [Strawhacker 2020]. In addition to demonstrating the accessibility of CRISPEE to the majority of children who played with it, the fact that more solo-play children mastered the tool interactions highlights the importance of individual play time with the tangible tool to support children's meaningful engagement with novel tangibles. Regardless of whether they fully mastered the tool, all children in the museum found CRISPEE engaging and fun, and wanted to play with CRISPEE for longer than the 10-minute play session (see Figure 1).

Four camp students (ranging in age from 5-8 years) and a research assistant all work together on a CRISPEE program. (© author's personal photos)

At the Children's School, a small group of 8 children and several teachers engaged in a week-long bioengineering-themed vacation camp using CRISPEE, and a curriculum and learning supports (e.g. a picture book, classroom anchor charts) all designed to introduce the ethical bioengineering design process (Strawhacker, Verish, Shaer, & Bers, 2020b). Children's interactions with CRISPEE, their engagement during curricular activities, and their conversations with peers and teachers were all analyzed for evidence of their learning throughout the week. Children engaged with life science topics and engineering design practices. They connected their play and storytelling with CRISPEE to conversations about biology, hardware and software, animals and habitats, and environmental activism. Finally, all children culminated their time in the camp by imagining a creative solution using CRISPEE that could help humans or animals. Some of their ideas included using genes to protect endangered species and prevent or clean up pollution (Strawhacker, 2020). Just like at the museum, children in the camp were motivated to play with CRISPEE, and found the tool exciting and engaging throughout the whole week, even requesting to come play with the toy for several weeks after the camp ended (see Figures 2-3).

Children and teachers at the camp played with CRISPEE as one among many bioengineering-themed centers and activities. (© author's personal photos)

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Cognitive Perspective

Cognition is increasingly understood as a process that together engages the brain, the body, and the physical and social environment. As such, TEI researchers have drawn heavily on theories from the cognitive sciences, such as distributed, embodied and situated cognition [Hutchins 1995; Kirshner and Whitson 1997; Shapiro 2011], and have used them to inform the design of interactive systems that bring together human bodies, physical spaces and artifacts, and computational media. Chapter 4 looks at some of the cognitive theories that inform TEI design in greater detail. In this section, we focus on cognition as a perspective on the evaluation of TEI systems. While the user interaction perspective considers the usability and user experience of TEI systems, evaluation from a cognitive perspective focuses on the ways in which a TEI system can impact a user's cognition. Although there is some similarity in methods, the goals and some of the instruments and measures differ when considering evaluation from a cognitive perspective.

In some cases, researchers use cognitive assessment tools pre- and post-task to understand the impacts on cognition of a particular TEI intervention, often in comparison to other interface conditions and/or to some other baseline. These tests are designed to assess different aspects of cognition, such as working memory, verbal comprehension, perceptual reasoning, processing speed, and various spatial abilities. Examples include the Wechsler Intelligence Scale for Children (WISC) [Wechsler 2014], and different spatial ability tests such as the Vandenberg & Kuse Mental Rotation Test [Peters et al. 1995; Vandenberg and Kuse 1978] and the Perspective Taking and Spatial Orientation Test (PTSOT) [Hegarty and Waller 2004]. Other pre/post-test methodologies assess conceptual change and learning impacts, such as in the Teegi [Fleck et al. 2018] example discussed above. Some researchers also use coding and analysis of video recorded interactions to understand how users' behaviors with a TEI system affect their cognition. For example, Esteves et al. [2015] developed the Artifact, Body, Tool (ATB) framework, a video-coding framework for identifying and measuring different epistemic actions during TEI problem-solving tasks. The coded actions are used as a performance metric to assess tangible systems from a cognitive perspective. Additionally, researchers can consider how TEI systems support creativity and ideation by employing different measures such as fluency (number of ideas), flexibility (variety of ideas), novelty (rareness of ideas), and quality [Kerne et al. 2014].

We illustrate TEI evaluation from a cognitive perspective by describing two examples: a comparative study that used a pre/post-test method to assess the impact of a tangible system

Figure 7.3 User evaluation of the Tangibles for Augmenting Spatial Cognition (TASC) system [Chang et al. 2017a,c]. The system employs tangible and embodied interaction in virtual reality to engage users in a series of spatial puzzles that are designed to support and enhance their perspective taking spatial ability.

on spatial cognition [Chang et al. 2017c] and a comparative study that used protocol analysis to examine the cognitive impacts of a TUI vs. a GUI for 3D design [Kim and Maher 2008]. As in the previous section, we aim to highlight the evaluation methods used rather than the specific research results.

Tangibles for Augmenting Spatial Cognition (TASC) [Chang et al. 2017a] is a system that uses virtual reality with TEI (VR-TEI) to support and enhance a spatial ability known as perspective taking (i.e., the ability to mentally visualize different spatial viewpoints). In using the TASC system, users need to switch between different viewpoints in the virtual space and manipulate tangible blocks in order to solve a series of spatial puzzles (see Figure 7.3). In order to evaluate the effects of the TASC system on perspective taking [Chang et al. 2017c], the researchers employed a pre/post-test method in which participants were given the Perspective Taking and Spatial Orientation Test (PTSOT) [Hegarty and Waller 2004] before and after interacting with the TASC system. In addition to the TASC VR-TEI condition, the researchers included two comparative conditions: a GUI version of the system that used keyboard and mouse interaction for solving the same set of spatial puzzles and a control condition in which participants performed non-spatial tasks (e.g., typing text) for the same amount of time as the spatial intervention. The study employed a between-subjects design, with a total of 46 participants. Statistical analyses that looked at accuracy and precision were conducted on the pre/post-test scores in order assess comparative changes in performance across the three conditions.

TUI vs. GUI for 3D Design. In work by Kim and Maher [2008], a tabletop TUI for 3D design was compared against a corresponding GUI-based system as a baseline. The focus of the work was to evaluate the effects of the TUI system on designers' cognition. To this end, the researchers employed a protocol analysis method [Gero and Mc Neill 1998] to understand the cognitive processes that underlie a user's performance in the TUI vs. the GUI design conditions. Similar to the behavioral action-coding approaches described above, the protocol analysis method involves the coding and analysis of the participant's actions, the external representations produced by the participant, and the participant's verbal account of their work process collected using a think-aloud protocol. The study was conducted with seven competent designers who were all undergraduate students in architecture. Each participant completed one design task in the TUI environment and a second design task in the GUI environment. As noted by the researchers, empirical studies that look at designers' cognition often use a relatively small number of participants. In this case, as the data collected included a large number of data elements, the researchers had enough data to validate a quantitative analysis despite the small number of participants.

Dr. Audrey Girouard, Carleton University
The Necessity of Running Pilots

Researchers often spends weeks, months planning an experiment: we build a tangible prototype, we think about how to evaluate it, what questions to ask, who will be our target population. It is now ready to go. We schedule multiple participants per day for in the next few days to optimize data collection. The first participant arrives, and we realize that something is not going according to plan: perhaps the experiment is much longer than expected; perhaps participants are confused about what they are supposed to do; perhaps our prototype breaks because people are not handling it the way we had planned, anticipated. Is there something that can be done to prevent these situations?

Before running a study, whether an empirical experiment or a design method evaluation, it is critical that researchers run a pilot of the experiment. Pilots are complete run-throughs of the experiment, but with the mindset that you will throw out the data. Pilots will test whether your questionnaires make sense, whether you are collecting the right data, whether the data is logging properly. They will help you rehearse the procedure.

User testing your procedure, your instructions – Participants are normally blank canvases that simply follow your instructions, directly answering your questions as posed. When testing new technologies, even the tiniest steps need to be clearly explained. As such, you need to user test the instructions, as you may be skipping a step, unintentionally assuming knowledge from participants. My PhD student ran a study using an online ideation card deck, and pilot participants did not realize that they had to click a "Next Set" button to get more cards. A simple correction in the instructions (adding "click the button for the next set of cards") solved the problem.

You might also find instructions that need to be embedded in the design of the prototype. In a study with a new pen prototype, we were surprised to see how people would hold the pen. Some holds were not compatible with our data collection. Pilot testing allowed us to notice this, modify the pen to guide the user into specific holding positions, as well as make sure we recorded this holding pattern.

Evaluating your logged data – Are you logging everything? Is your algorithm to randomize or counter-balance conditions correct? Once, we had to discard data from over a dozen participants because the lack of randomization meant our data was unreliable. A very unfortunate situation. Another time, by looking at the logged pilot data of a multi-factorial experiment, we realized that most conditions generated 12 tasks (as planned), but a few generated 11 and some 13. It was a small coding mistake, but would have been problematic for our statistical analysis.

More advice – Plan for at least 2-3 pilots tests. They should be least a day apart, so you have time to fix things in between. You can have your first one be someone from your lab, but make sure to test with your broader study population (as your colleagues may help with the process but will not be agnostic to your study).

Dr. Audrey Girouard is an Associate Professor in the School of Information Technology at Ottawa's Carleton University, where she is also the Associate Director for Graduate Studies. She leads the Creative Interactions Lab and the Collaborative Learning of Usability Experiences training program. Specializing in next generation interactions, her current research focuses on deformable devices and wearables. Her work has applications in health, accessibility, gaming, creative input, and mobile devices. She sits on the steering committee for the ACM TEI Conference and was the Program Committee's Co-Chair in 2012 and 2018. She was awarded the CS-CAN Outstanding Young Computer Science Researcher Prize, the Carleton University Outstanding Faculty Graduate Mentoring Award, the Ontario Early Researcher Award, the Carleton University Research Achievement Award and the Partners in Research Technology Ambassador Award. Dr. Girouard received her PhD in Computer Science from Tufts University and completed a post-doctoral fellowship at the Human Medial Lab at Queen's University. Her undergraduate degree is in software engineering from École Polytechnique de Montréal.

Technical Perspective

TEI designs introduce new ways of interacting with computational systems that make use of a variety of mediating technologies, including physical sensing, display, actuation, and communication. These approaches are discussed in further detail in Chapter 5. Here, we look at how new interaction technologies are evaluated from a technical perspective.

In contrast to the user interaction and cognition perspectives described above, technical evaluation of mediating technologies does not focus on users. Instead, the primary goal of technical evaluation is to assess the performance of a given technology in order to validate its use in an interactive system. As many TEI systems use tracking technologies of some kind, accuracy is a primary measure that is used to evaluate them. A sensing system is

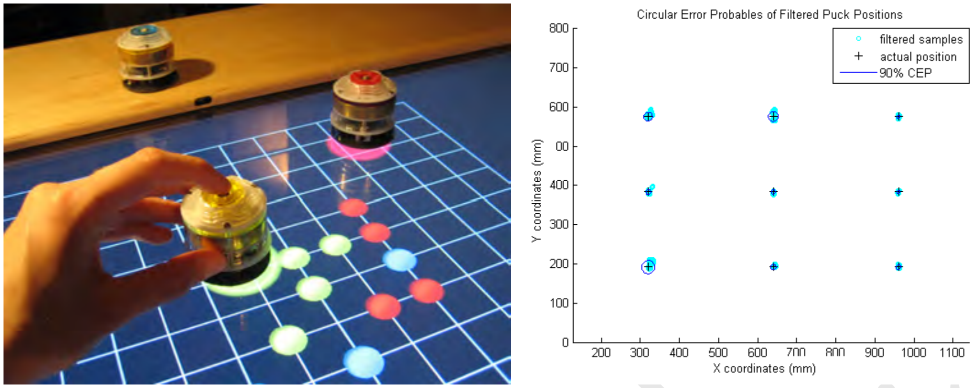

Figure 7.4 Left: the TViews Table [Mazalek et al. 2006] is a tangible tabletop interaction platform based on an acoustic-based object tracking system. Right: as part of the technical evaluation, the researchers measured the positioning system accuracy at a 100 Hz update rate [Reynolds et al. 2007].

accurate if repeated measurement values (e.g., of position) are close to the true value. Other common measures include precision, which looks at how close the values are to each other, and reliability, which looks at the consistency of the results, as well as the main factors that cause failure and the behavior of the system when it fails. A technical evaluation may also consider questions such as latency, power consumption, spatial resolution, scalability and more, which can all have effects on the system's use in real situations. Additionally, mediating technologies are often tested under different conditions in order to simulate their real-world use, e.g. different materials, lighting conditions, or sizes/distances may impact the performance of a particular technology.

As described in chapter 5, complementing the development of specific mediating technologies, there has been a significant amount of work focused on the creation of toolkits to support the design and development of TEI systems. These include hardware-based toolkits such as Phidgets [Greenberg and Fitchett 2001b] and Lilypad Arduino [Buechley et al. 2008a], as well as cross-device interaction toolkits [Brudy et al. 2019] such as the Responsive Objects, Surfaces, and Spaces (ROSS) API [Wu et al. 2012] and the Society of Devices (SoD) Toolkit [Seyed et al. 2015]. As described by Ledo et al. [2018], the main strategies for evaluating toolkits are: 1) demonstrations that show what the toolkit can do, 2) studies of usage that assess how developers can use the toolkit, 3) analysis of technical performance based on certain benchmarks, and 4) inspection against a set of toolkit-centric heuristics.

We illustrate TEI evaluation from a technical perspective by describing three examples: the TViews Table [Mazalek et al. 2006; Reynolds et al. 2007] acoustic-based tracking system for interactive surfaces, the GravitySpace [Bränzel et al. 2013] pressure-sensitive floor-based

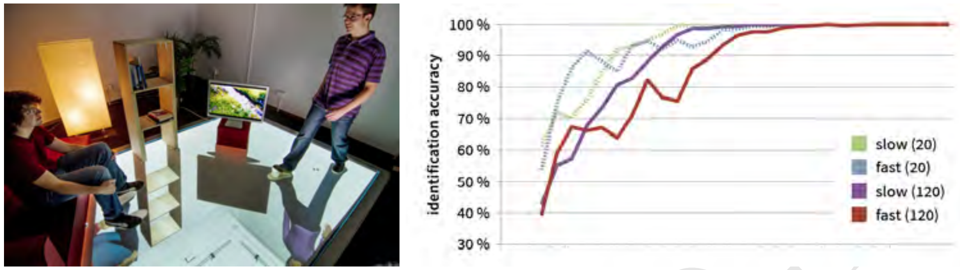

Figure 7.5 Left: GravitySpace [Bränzel et al. 2013] is a pressure-sensing floor that can track people and furniture. Right: as part of the technical evaluation, the researchers measured the accuracy with which the system could detect slow and fast walking users based on a dataset of 20 vs. 120 identifying shoeprints [Bränzel et al. 2013].

tracking of people and objects, and the ZeroN [Lee et al. 2011b] actuation system for mid-air tangible interaction. We highlight the technical evaluation methods used rather than the specific research results.

The TViews Table [Mazalek et al. 2006] is a tangible tabletop interaction platform based on a custom designed acoustic-based object tracking system [Reynolds et al. 2007]. The sensing system is based on acoustic transmitters affixed to the corner of a protective glass surface that sits atop a horizontally placed LCD display, and tangible interaction objects, each containing a receiving transducer, that can be manipulated on the glass surface. The researchers conducted experiments to characterize acoustic wave propagation in the protective glass, as well as the signal at a receiving transducer. In order to evaluate the performance of the system, they measured the achieved positioning accuracy at a 100Hz update rate at nine positions that were evenly space over the display surface (see Figure 7.4), and also discussed sources of error during positioning, as well as possible strategies to mitigate the errors. Additionally, they reported power consumption of the battery-powered receiving objects in order to determine the approximate continuous tracking time provided by the system.

GravitySpace [Bränzel et al. 2013] is a pressure-sensing floor for smart rooms that can track people and furniture that come in contact with the floor, and draw some conclusions about what happens in the space above the floor, such as a user's pose or activities that happen on top of specially-tagged furniture. The system is based on Frustrated Total Internal Reflection (FTIR) [Han 2005a] by using a camera placed below the floor. Pressure clusters are classified based on image analysis and furniture is identified based on visual markers. The system can also make predictions, such as pose recognition based on spatial configuration of clusters. The researchers conducted a technical evaluation that assessed the system's accuracy in terms of distinguishing different body parts on the floor, recognizing body poses, and identifying users based on shoeprint matching. For user identification, for example, the researchers recruited 20

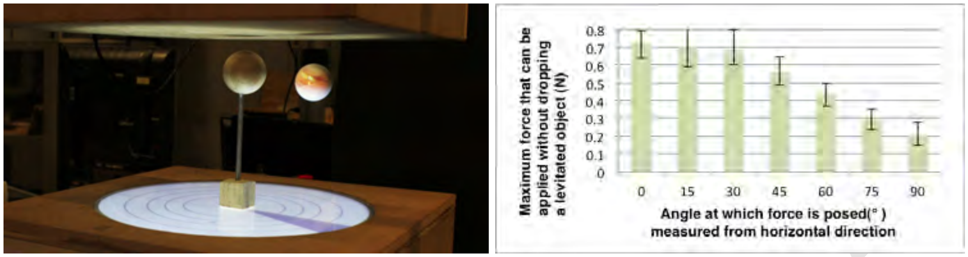

Figure 7.6 Left: ZeroN [Lee et al. 2011b] is a mid-air tangible interaction system that uses magnetic control to levitate an object coupled with optical tracking and display. Right: as part of the technical evaluation, the researchers measured how much force can be applied to the object while still keeping it in suspension [Lee et al. 2011b].

users to walk on the floor so that the system could select left and right shoeprints for each user. Next, they collected test data by asking the same users to walk slow or fast, and then assessed the accuracy with which the system could identify each user against the small dataset of 20 users, as well as against a larger dataset of 120 users that included data from 100 additional lab members and visitors (see Figure 7.5).

ZeroN [Lee et al. 2011b] is a system for mid-air tangible interaction that uses a magnetic control system to levitate and actuate an object containing a magnet within a predefined "anti-gravity" 3D volume. An optical tracking and display system can project graphics onto the levitated object, and users can interact by grabbing, rotating, and moving the object in the anti-gravity space. In order to evaluate ZeroN from a technical perspective, the researchers considered a number of factors and also reported on the system's limitations. Factors included: the maximum range of levitation which is limited by the heat generated in the electromagnet's coils, the system resolution which is limited by the lateral oscillation of the object, and the speed of actuation which limits how fast a user can move the object before it drops. Additionally, the researchers tested the robustness of magnetic levitation by experimentally measuring how much force can be applied to the object without displacing it from stable suspension (see Figure 7.6).

Arts Perspective

The arts have played an important role in TEI from the outset. Indeed, the first International Conference on Tangible, Embodied and Embodied Interaction in 2007 explicitly aimed to bring together multiple disciplinary perspectives, including researchers, designers, practitioners and artists. By 2011, the conference introduced a separate arts track for the presentation of interactive artworks that explore different aspects of TEI from an artistic perspective.

Figure 7.7 Left: Architales [Mazalek et al. 2009] is a an interactive story table that was shown at the Listening Machines 2008 show at the Eyedrum Gallery in Atlanta, GA, USA. Right: Though Miles Apart [Sungkajun and Seo 2019] is an interactive installation that uses a soft interface to engage visitors in the act of reminiscing.

When considering evaluation from an artistic perspective, we can look at how visitors experience interactive artworks that employ TEI techniques. Indeed, many TEI artworks have been exhibited in art galleries, and in some cases the creators have observed visitor interactions and gathered feedback, which they have used to formulate lessons that can inform future works. This kind of informal evaluation can be seen in examples such as Architales [Mazalek et al. 2009] and Though Miles Apart [Sungkajun and Seo 2019] (see Figure 7.7). In other cases, the artist-researchers (or in some cases researchers working with professional artists) have studied the creative process and/or the visitor experience of the created work in a more formal way. These studies typically use qualitative approaches such as ethnography, and data is collected through observations and interviews. However, the focus is not performance-oriented, and in contrast (or sometimes in addition) to the questions of usability and user preference described above, the researchers might ask, for example, what motivations and intentions shaped the construction of the work, how closely the visitor interactions relate to the artist's motivations and intentions for the work, or how the visitors' interactions unfold in a public setting. Morrison et al. [2007] draw on William Gaver's [2002] concept of designing for "ludic" engagement to describe these kinds of evaluations of interactive artworks, which prioritize pleasure over function, as well as subjective interpretation and ambiguity as positive values for the design of interactive experiences [Gaver et al. 2004].

It is important to note that evaluation from an artistic perspective accounts not only for the way in which artworks are created and experienced, but also for the role these works play in supporting a critical examination of TEI as a medium [Tomás 2017]. Indeed, numerous researchers have called for the integration of art criticism with HCI methods (see e.g., [Höök et al. 2003; Morrison et al. 2007]) for evaluating engagement with interactive artworks. Tomas [2017] extends Søren Pold's [2005] concept of the "critical interface" to suggest that

Figure 7.8 Left: Day of the Figurines [Benford et al. 2011] is a interactive performance and installation piece that uses a tabletop spectator interface to visualize an unfolding narrative over time. Right: tangible figurines are selected by participants to represent their characters on the spectator interface.

the creation of TEI artwork can serve to critically reflect on accepted assumptions within HCI design, as well as to propose alternate models for evaluating the experiential aspects of interactive experiences. The goal is less about providing clear answers and functional solutions, and more about opening up new questions and different ways of seeing.

We illustrate TEI evaluation from an artistic perspective by looking at two examples: an ethnographic study of the creation and experience of the Day of the Figurines interactive artwork [Benford et al. 2011] and the critical examination of the Tangible Scores expressive musical interface [Tomás 2016, 2017; Tomás and Kaltenbrunner 2014].

Day of the Figurines [Benford et al. 2011] is an interactive experience by the professional arts group Blast Theory that is both public performance and installation piece. The piece unfolds over 24 days as participants experience an interactive adventure – a day in the life of a fictional town – via text-messaging. A corresponding tangible spectator interface hosted by a local art gallery provides an ongoing visualization of the unfolding narrative (see Figure 7.8, left). Each participant's character is represented by a tangible figurine (see Figure 7.8, right) on the tabletop spectator interface, and operators stage a performance every hour over the course of the 24-day experience in which they update the positions of the figurines on the table to reflect current state of the narrative. As Day of the Figurines toured to different cities around the world, HCI researchers conducted an ethnographic study to understand the work of the artists in designing and installing the piece, as well as the experience of the participants who engaged with the piece. To do this, the researchers conducted more than 10 site visits to different venues where the work was deployed in order to document the action that took place at different points in time – leading up to, at the beginning of, during, and at the end of the experience. They collected video recordings and conducted informal unstructured interviews with participants,

Figure 7.9 Left: Tangible Scores [Tomás 2016, 2017; Tomás and Kaltenbrunner 2014] are laser-engraved wooden surfaces that are both digital instrument and musical score. Right: an interactor can explore a Tangible Score through tactile interactions.

and well as with the artists and in-gallery operators. They then did an ethnomethodological analysis of the captured events, aiming to uncover key themes that address the rationale and craft of the artists, as well as the interactive experience of the participants.

Tangible Scores [Tomás 2016, 2017; Tomás and Kaltenbrunner 2014] are laser-engraved wooden surfaces that serve as both digital instrument and musical score, and that can be explored with gestures like tapping and scratching (see Figure 7.9). In keeping with the idea that TEI artworks can serve critical interfaces as described above [Pold 2005], the artist-researcher reflects on the way in which Tangible Scores question fundamental aspects of interface design in electronic music, such as the abundance of symbols and parameters that must be learned, and foreground new ideas, such as the way users must "think the materiality" [Tomás 2017]. Additionally, he reflects on the work from the perspective of practice-based research, where the contributions to knowledge emerge through his own practice with the interface (e.g., concerts with the work, composition).

Philosophical Perspective

TEI is rooted in theories of embodiment that focus on the study of human experience in the world, such as the branch of philosophy known of phenomenology that was founded by Edmund Husserl in the early 20th century, and further developed by philosophers such as Martin Heidegger, Alfred Schutz and Maurice Merleau-Ponty. While the central ideas of phenomenology are described in greater detail in Chapter 4, here we look at how philosophy can inform the evaluation of TEI systems.

Winograd and Flores [1986] were central in bringing ideas of phenomenology to HCI by drawing on Heidegger's concepts of *ready-to-hand* and *present-at-hand* to describe the way our relationship with objects changes in the event of a breakdown. Since then, numerous researchers have discussed how phenomenology can serve as a framework for the interpretation

Figure 7.10 Breeze [Coffin 2008] is a robotic live Japanese maple tree that can sense the presence and movement of people in its environment and respond by moving its limbs.

of HCI systems, particularly those that employ TEI approaches. Dourish [2001a], for example, has argued that phenomenology can serve to frame our understanding of embodied interaction, particularly in the context of tangible and social computing. In related work, Svanæs [2013] has drawn on Merleau-Ponty's ideas about perception and the lived body to suggest several concepts that can be used in the analysis of interactive systems: the *feel dimension* of HCI, *interaction gestalts*, and *kinaesthetic thinking*. He notes that these ideas can be helpful in considering the "feel" of user experiences, as well as the role that the kinaesthetic sense plays in the design of interactive systems.

Moving beyond phenomenology, another useful lens for the evaluation of TEI systems is that of postphenomenology, which is an empirically oriented philosophy of technology that focuses on concrete human experiences with technology [Ihde 1995; Rosenberger and Verbeek 2015b]. As such, postphenomenology provides a way to analyze the particularities of technologies and the ways in which they shape our day-to-day lives. A key analytical concept from postphenomenology that can be applied to TEI is the idea of "multistability" [Ihde 2012; Jensen and Aagaard 2018; Van der Zwan et al. 2020], which points to the multiple possible uses a technology can have in different contexts. Another important concept is that of mediation [Jensen and Aagaard 2018], which alludes to the agency of a particular technology. These concepts can be applied in the analysis of TEI systems in different ways. For example, Jensen and Aagaard [2018] apply the "variational cross-examination" approach developed by Rosenberger [2014] to TEI designs. The central idea of this approach is to identify and contrast the features of an artifact's multiple stabilities. In other work, Kiran [2015] describes four dimensions – the practical, the ontological, the epistemological, and the ethical – that can be used to characterize technological mediations. Some researchers also propose moving from an empirical approach to a more practical one, in which postphenomenological theories and methods are used to improve design outcomes [Eggink and Dorrestijn 2018; Van Belle et al. 2019]. For example, Van Belle et al. [2019] describe a Philosophy-through-Design (PtD) process that is guided by a philosophical research question. Questions, creations and reflections

Figure 7.11 coMotion [Grönvall et al. 2014b; Kinch et al. 2014a] is a bench that can change its shape in response to the people who sit on it.

in the PtD process interact with each other, yielding contributions to philosophy and to design by opening up new questions and perspectives rather than by finding answers. Also, Kiran's [2015] dimensions have been applied as a generative lens in design research and practice [Van der Zwan et al. 2020].

We illustrate TEI evaluation from a philosophical perspective with two examples: the phenomenology-based interpretation of an interactive artwork called Breeze [Coffin 2008], and the postphenomenological analysis of the coMotion actuated bench [Jensen and Aagaard 2018; Kinch et al. 2014a]. Our focus here is on how philosophy informed the interpretation of these works.

Breeze [Coffin 2008] is an interactive artwork consisting of a robotic live Japanese maple tree that senses and responds to the presence and movement of humans in its environment (see Figure 7.10). The piece uses nitinol-based muscular systems to actuate the flexible maple limbs, and human movements around the tree are sensed by a 360 degree camera and a radial ultrasonic sensor array. The piece was exhibited at the Belluard Bollwerk International Festival in Fribourg, Switzerland in 2006. During the exhibition, Coffin (the artist), along with her collaborators and the festival administrators, documented the spontaneous behaviors of visitors interacting with Breeze. Coffin [2008] then used phenomenology to interpret the interactive piece and its experiential attributes. For example, she used Heidegger's concepts of *Lichtung* and *Verhalten* to understand the experience with Breeze as an open field of interaction possibilities in which emergent and performative behaviors can occur.

The coMotion Bench [Kinch et al. 2014a] (see Figure 7.11) is a shape-changing bench consisting of three interconnected sections whose height and angle can be adjusted to alter the bench's overall shape into different configurations (e.g., completely flat, V-shaped, etc.). The bench reflects its intentions through its changing shape, which is a response to where people seat themselves. For example, when two people sit at opposite ends, the side sections of the bench will tilt down toward the center (V-shape), thereby pushing the people together to encourage a brief encounter. Using data gathered in Grönvall et al.'s [2014b] user study of the bench in three different locations, Jensen and Aagaard [2018] conducted a postphenomenological analysis of the coMotion bench using cross-variational analysis. In doing this, they addressed three features of the bench's multiple stabilities: 1) comportment and habits, 2) role within a program, and 3) concrete tailoring. *Comportment and habits* looks at the bodily experiences and habits associated with the bench's different stabilities (i.e., it can act as a regular bench, but also has a shape-changing stability). *Role within a program* looks at how different stabilities play out in specific contexts among specific people. Lastly, *concrete tailoring* looks at the materiality of the bench and how this impacts people's experiences. Overall, the postphenomenological analysis helps to uncover the importance of the bodily experience in human interactions with technology, particularly when the technology behaves in unexpected ways.

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Cross-Fertilization Between Design and Philosophy

As a philosopher of embodied cognition, I am interested in the active role of the environment in shaping everyday human activities. It was not until starting my post-doc with Caroline Hummels at Eindhoven Technical University that I began to understand the potential for design to contribute to an answer to this topic. I encountered a research field that based itself on the same principles as I did in my own work: phenomenology and Gibson's theory of affordances. Moreover, I encountered a kind of methodological consistency that is sometimes missing in philosophy: if one takes seriously the idea that we are not *thinking things* but *thinking with things*, then why not explore, change, adapt and design these things? The TEI-community might think that reading Heidegger can make you a better designer, but perhaps being a good designer can make you a better "Heideggerean" as well.

Perhaps then the contribution of TEI to philosophy is not a set of design artefacts in line with a particular philosophical view (this would be kind of boring). Instead, the contribution lies in methods, in material speculation and in a continuous conversation in which designers and philosophers can challenge and inspire each other.

I think such cross-fertilization between philosophy and design has been most productive in the field of postphenomenology [Verbeek 2005], where it has been used as a lens to analyse how a design mediates the experience of its users [Hauser et al. 2018a], and as a generative lens to inform the design process [Van der Zwan et al. 2020]. However, there is ample room for expansion. Understanding how a concrete artefact in use mediates experience is one thing, but everyday activity involves the continuous switching between different technologies. While reading *Sein und Zeit*, my phone affords to be picked up, and once picked up, it affords a whole range of activities. It is an open question how to make sense philosophically and phenomenologically of the ubiquity of digital devices in our life-world (with some of these technologies explicitly designed to capture our attention [Williams 2018]). How to design such a layout of affordances and what is a good layout?

It might help to understand such situations in terms of coordinating with a "field of affordances" (those affordances that stand out as relevant for a particular individual in a particular situation [Bruineberg and Rietveld 2014]). Some of these affordances are focal (*Sein und Zeit*, a pencil and coffee), while others are on the periphery (my phone and all the affordances it offers). Importantly, the field of affordances does not respect the boundaries of a technology: once I pick up my phone, my experience of the world might be mediated in complex ways, but the book did not disappear from the field, it merely shifted out of focus.

One example of how the layout of affordances can structure everyday activities is provided by RAAAF | Barbara Visser. Their art installation *The End of Sitting* (see Figure 1) offers a landscape of affordances for supported standing, in the sense that surfaces afford working in several non-sitting postures. Because the muscles used in any position will get tired, it will make people switch to different places in the landscape. By analogy, it might be helpful to not just consider one design in use, but the way multiple designs and technologies make up a layout of affordances through which a user navigates during the day.

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Summary

Researchers in HCI have argued that the past couple of decades have seen the rise of a third paradigm that extends the field beyond its initial engineering and later cognitivist roots [Bødker 2006; Harrison et al. 2007, 2011]. The area of TEI, along with related areas of research such as pervasive and ubiquitous computing, are at the core of this third wave. While the first and second paradigms of HCI focused on human factors and information processing, respectively, the third paradigm extends from a phenomenological perspective, and shifts toward interaction spaces that are, by their physical and social nature, inherently more dynamic and complex, and in many cases less task-oriented. Crucially, as Harrison et al. [2007] note, this shift in paradigm not only represents alternative ways of thinking about and designing human-computer interactions, but also requires new methods for evaluation, particularly ones that are context-dependent and value-based.

In the above section, we provided five different perspectives on the evaluation of TEI systems that cut across the numerous disciplines that are engaged in TEI research and design. As we have noted, these perspectives are not intended to be mutually exclusive, nor do they form a comprehensive set. Rather, we hope they can serve as inspiration to view the evaluation of TEI designs from a broad set of viewpoints. As we turn in the next chapter to aspirations for the field, we expect that going forward, the current and emerging generation of TEI practitioners will help to further expand on the perspectives and approaches for evaluating work in TEI.

8 Paths Forward: Aspirations for TEI

In this chapter, we draw upon the conceptual, cognitive, and technical foundations laid earlier in this book as well as the review of TEI in the wild, to suggest paths forward – aspirations and an agenda for TEI practice, research, design, and development. There are many facets to our contemplation of "agenda;" among these, a plan and framework, consistent with the definition of agenda as a "thing to be considered or done" [Webster 2008]. The agenda we propose here is not restricted to the field of TEI, but rather celebrates and promotes entanglements interweaving traditionally-disparate disciplines, communities, and organizations. In the process, we hope to inspire researchers, innovators, and broader audiences to design, develop, and apply both established and novel TEI systems and technologies with positive societal impact. We also endeavor to highlight the importance of vision-driven research as articulated by [Ishii et al. 2015c], which seeks to both engage and transcend functional goals.

Our aspiration is to bring in diverse perspectives for TEI to foster healthier, sustainable and more fulfilling lives for individuals and communities by leveraging and augmenting humans and their environment to enhance creativity, productivity, collaboration, learning, imagination, inquiry, and connectedness. This will most certainly not be one-size-fits-all. On the contrary, our perspectives envision and engage a world that sometimes holds more graphical displays, and sometimes fewer; sometimes more human "input," and sometimes less; sometimes "more technology," sometimes less, with manifestations sometimes more in the background, and sometimes less. In some cases, the artifacts we have described take on forms relatively generic across cultures. In others, we aspire to culturally specific forms, of idiosyncratic materials, reflecting and embodying cultural legacies spanning hundreds or thousands of years. We envision a rich world of interaction, created by many people of diverse experience and expertise. In the following, we highlight a few directions toward fulfilling such aspirations. In particular, we articulate an agenda for TEI research, design, development, and practice, which is structured around three facets:

- *Deep engagement with societal challenges:* here, we advocate developing and applying novel and established TEI systems, technologies, tools, methods, approaches and theories that anticipate and explore changing paradigms and that address grand societal challenges, such as those formulated in the United Nations Sustainable Development Goals [Nations]. These include pressing problems such as equal rights; eliminating poverty; providing quality education to all; planning and building inclusive; sustainable communities; and improving health and well-being.

- *Fostering synergies across scientific, technology, engineering, art and design (STEAM) advances:* we advocate forming partnerships to promote scientific discovery and technical innovation and for creating 'tools for thought' that augment human cognition and creativity, turn data into insight, and support new forms of collaborations that bring together not only people but also other cognitive entities such as AI systems and robots.
- *Envisioning socio-culturally embedded TEI communities:* from its inaugural year, the TEI conference and community were organized to express respect to a broad spectrum of constituent disciplines, with openness toward showing and sharing 'crazy' new ideas, and emphasizing opportunities for mutual learning, be it on practical toolkits, insightful user studies, stunning engineering, aesthetic, poetic or even shocking experiences, and deep philosophical questions. This attitude and new innovations are all the more needed, seeing the long-term societal challenges all of humanity – and indeed, our global ecosystem – are facing regarding (e.g.) sustainability and well-being, as well as current challenges such as Covid-19 and pressing need for eliminating racism and ensuring equal human rights advanced through movements as Black Lives Matter.

We expect that applying TEI approaches to addressing such challenges will require continuing to push the boundaries of TEI by inventing new interaction techniques, novel design media, and different interactive technologies. Such advancements will also require developing new paradigms and theories for the design, interpretation, application, and evaluation of TEI.

Deep engagement with societal challenges and changing paradigms

Moving toward new paradigms

Novel interdisciplinary efforts are required to address current societal challenges such as eliminating racism, decreasing poverty, providing quality education to all, ensuring healthy and fulfilling lives, and making communities inclusive, safe and sustainable. These efforts focus on the development of new systems, technologies, and ways of interacting with the world, but they also push us towards new paradigms – new shared beliefs, values, models and exemplars to guide a community of practitioners and theorists [Kuhn 1963] toward sustainable futures.

Over the last 40-50 years, several underlying paradigms and types of societies have been noted, including the industrial society [Williams 2003], experience economy [Pine et al. 1998], network society [Castells 1996; van Dijk 2001], information economy and society [Crawford 1983; Porat 1977], service economy [Shelp 1981], and the performance economy [Staher 2006]. Recent paradigms often focus on tackling societal challenges, as captured in the circular

Figure 8.1 Design fictions Digitarians (left) and Communo-nuclearists (right), two experimental county zones with their own form of governance, economy and lifestyle in the United Micro Kingdoms (UmK. Design fictions are merging science, design and fiction, and they use storytelling to question the world around us and they use a combination of concepts, objects and visuals to propose for how things could be otherwise [Dunne and Raby 2013b] (GI: Tomasso Lanza).

economy [Pearce and Turner 1990], the transformation society and economy [Brand and Rocchi 2011; Pine et al. 1998] and the purpose economy [Hurst 2016].

These latter paradigms offer compelling possibilities for the TEI community, because different paradigms often invite and call for different questions and answers; different relationships and interactions with the world, for different theories, models and frameworks; different design processes, methods and tools; as well as different disciplines and stakeholders with different competencies. Considering the multi- and transdisciplinary perspective of TEI and its potentials for providing more intuitive, collaborative, and effective ways to people to interact with each other and the world in various domains, it is important to examine how TEI can address pressing societal problems through systems, technologies, tools, methods, and theories.

The creation of new meaningful innovations requires an understanding of changing values and paradigms. One way of creating this understanding is by departing from the emerging present and pursuing an understanding (via weak signs[1]) of how value is changing for people and how socio-cultural paradigms are developing. Based on an understanding of our current changes, we might project towards things to come [Rocchi et al. 2018]. Developing various (research) prototypes, design probes and even speculative designs can initiate a debate about these values and paradigms, and explore how products and services could help people to achieve their future goals and aspirations [Dunne and Raby 2013b; Kolkman; Wakkary et al. 2015b] (examples are shown in Figures 8.1 and 8.2).

But what will this future entail, where will we stand in 30-40 years' time and what could be the role of TEI? Will we strive through new technologies for endless repairs and enhancements

[1] Weak signs are "internal or external signals that can alert an organization of potential threats and opportunities"[Dutton and Ashford 1993; Rerup 2009]

Figure 8.2 Material speculation uses situated design artifacts in the everyday context as a form of critical inquiry. Two examples: Table-non-table (left) [Wakkary et al. 2015b] and Tilting Bowl (right) [Wakkary et al. 2018b].

of our bodies and the environment? Will we aim at doubling our life expectancy or even immortality? Will we aim at having sustainable prosperity and dignified living for all, and live in harmony with nature? Or will TEI die a slow death and will society embrace a post-biological, post-human future, where biology and the human body are seen as a limiting factor, and intelligence is seen as the main goal [Harari 2018; Kolkman et al. 2018]?

We don't have the answers, although the latter scenario is not our preference. It is crucial that we all take an ethical stance when developing TEI. Or as Peter-Paul Verbeek Verbeek [2006b] says, "engineers are doing 'ethics by other means': they materialize morality." With this in mind, we must have these ethical debates about the kind of designs and interactions we are developing and the impacts they have on society.

Envisioning our society in 30-40 years is not the only way to address and explore this ethical stance. We are currently living in turbulent times, where the Covid-19 pandemic gave a completely new perspective on our society, our current values and paradigms, our patterns of behavior, our policies, etc. Suddenly our technology offered new ways of mediation, our social relationship with people changed, and the underlying embodiment principles of TEI where challenged by a 1.5 meter / 6 foot social distancing policy, as we also indicated in the summary. And only a few months later, when almost having finalized this book, ready for publishing, another pandemic called racism inflamed again due to the death of George Floyd, putting equality and human rights back at the center of everyone's attention. How can TEI address this pressing societal challenge and use its creative and constructive power to support a shift towards a new paradigm and a different ethical stance?

In this section, we sketch a few directions where we see TEI is already contributing or could contribute to address our societal challenges.

Addressing societal challenges

The UN Sustainable Development Goals (SDG) are set to move towards a better and more sustainable future for all within the upcoming decade [Nations]. The SDGs cover a large variety of topics including poverty, inequality, climate, education, peace, and justice. Not all of these goals will be tackled through TEI, but a few might benefit from endeavors within the TEI community. For example, in Chapter 2 we discussed TEI for health and wellbeing, which has ties with the third SDG, "good health and wellbeing." In this section, we address two global challenges: making communities inclusive, safe, resilient and sustainable, and lifelong inclusive learning for all, and we elucidate with examples how TEI might help.

TEI for making cities and communities inclusive, safe, resilient and sustainable

A wide range of TEI systems aim to democratize planning by making complex problem-solving more accessible to non-experts through modeling and simulation, and engaging different stakeholders in discussions around the planning and building of sustainable communities. In Chapter 1, we described early examples of TEI systems, developed starting in the late 70s, for urban planning and architecture, including the Building Block System (BBS) [Noakes and Aish 1984] and the Universal Constructor [Frazer et al. 1989]. Aish and Noakes, who invented the BBS, described their aspiration for the system: "This [BBS] can be expected to develop into a greater understanding by both professional and laypeople of the complex underlying relationships which exist between design, performance and perceptual variables that characterizes architectural design."

A few decades later, Hiroshi Ishii's Tangible Media Group has developed a number of functional prototypes that demonstrate how a wide range of interactive media with varying properties allow users to engage with complex simulations in intuitive ways. While early prototypes, including URP [Underkoffler and Ishii 1999c] (shown in Figure 8.3), allowed users to explore basic simulations like city planning using discrete tangible objects, later prototypes employed rich malleable materials including sand [Ishii et al. 2004] and clay [Follmer and Ishii 2012; Follmer et al. 2011; Piper et al. 2002] (shown in Figure 8.3) to support users' interaction with complicated simulations. Recent prototypes explore the vision of 'Radical Atoms' which we discuss in Chapter 3, by employing dynamic actuated materials that reflect real-time changes in an underlying computational simulation. For example, the Tangible CityScape [Tang et al.] (shown in Figure 8.3) system facilitates an urban massing process through an actuated shape display integrated with a digital shadow display and a gestalt view display.

Recent examples of TEI also focus on the collaborative and meaning formation side of planning and on participatory placemaking. Places can be seen as an interpretation of geographical spaces, which Holt-Jensen defined as 'territories of meaning' [Holt-Jensen 2018]. When zooming out and looking at spaces, we can discern three ways to understand spaces: conceived space (i.e. a representation of space); perceived space (i.e. spatial practice); and lived space

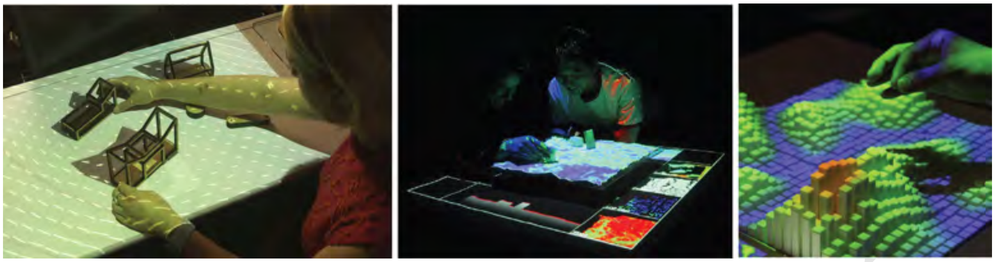


Figure 8.3 (a) URP, a prototype that allows users to explore basic simulations of urban planning; (b) Illuminating Clay, a project that facilitates interaction with complex simulations; (c) Tangible CityScapes, an actuated shape display that simulates an urban massing process [Tang et al.]. Images courtesy MIT Media Lab.

(i.e. the experience of spaces in the everyday life of users) [Lefebvre and Nicholson-Smith 1991; Soja and Chouinard 1999]. In the past, TEI seemed to develop tools that mainly helped to explore conceived and perceived spaces. However, lived places dive more into the meaning of space. "Places are spaces that you can remember, that you can care about and make part of your life" [Lyndon and Moore 1994]. Placemaking is the process of transforming spaces into places, which includes the social dimension of planning and which links function and meaning to the spaces [Cilliers and Timmermans 2014]. For TEI this means an expansion of tools that emphasize placemaking and meaning.

For example, the ColorTable (shown in Figure 8.4) [Maquil et al. 2008] is a tangible user interface which utilizes paper-based and simple tangible objects to support urban planners and diverse stakeholders in co-construction of ad-hoc mixed-reality scenes. The interface was used in a series of workshops for co-design that were held on site.

Focusing on engaging children in learning about placemaking and the impact on our interaction with the world, Youtopia [Wise et al. 2015b] (shown in Figure 8.5) is an educational tabletop tangible user interface designed to engage elementary school children in collaborative sustainable land-use planning and placemaking. Using Youtopia, children were invited to design their own world, exploring how different decisions about land-use impact the amount of food, housing and energy provided to the population, and the level of pollution in the environment. A predecessor of Youtopia, a tabletop game called Futura [Antle et al. 2011], was designed to engage the public with issues of sustainability. It was deployed in the 2010 Vancouver Winter Olympics (Canada) demonstrating that the general public can develop basic awareness outcomes around sustainability issues through collaborative participation in playful activities.

Another example, for discussing public issues at a community scale (i.e. meso scale) is Changing Perspectives ([X]CP) by Philémonne Jaasma [Jaasma and Wolters 2017], a product-

Figure 8.4 ColorTable, a table-based interface that supports co-construction for urban planners and other stakeholders [Maquil et al. 2008]

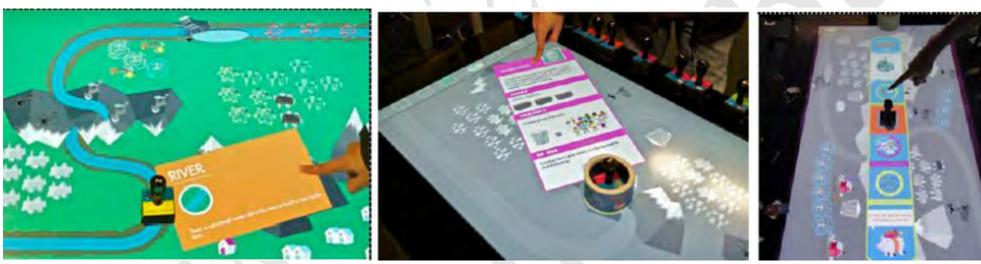


Figure 8.5 Youtopia, a collaborative land-use planning activity on an interactive tabletop. Children can explore the impact of their decisions using tangible tools that pause interaction and enable shared attention to information overlays about the state of the world and causes and effects during interaction. (a) Impact tool, (b) land use stamp & error tab, and (c) land use information ring (Photo Credit: Amanda Hall). [Antle et al. 2013c].

service-system (PSS) that uses fifteen interactive discussion tables with tangible tokens and real-time visualization to support citizens' resiliency and active contribution to the public good (shown in Figure 8.6). Up to 120 stakeholders can discuss a public issue by repositioning tokens and creating and sharing collective landscapes of meaning. [X]CP has been deployed in more than 15 real-life sessions, and at this point 40 interactive tables have been commercially developed and produced.

Placemaking can also be done directly in the community, with tools that allow for connecting function and meaning directly to the space. For example, Eric Paulos Paulos et al. [2009] have addressed sustainability not by simulation, but by directly using novel tools in

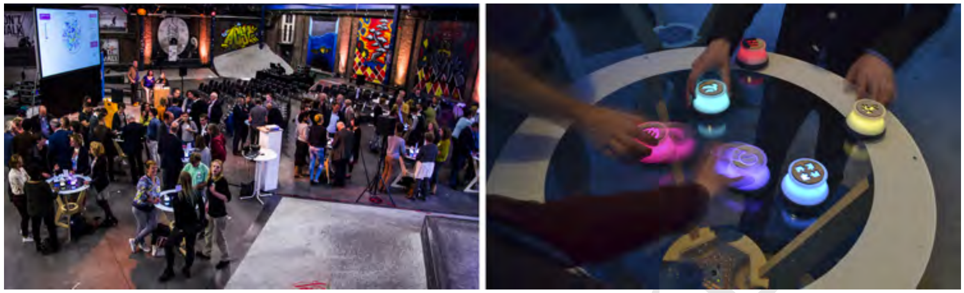


Figure 8.6 [X]Changing Perspectives enables up to 120 people to have a situated and embodied discussion [Jaasma and Wolters 2017] (Photos made by Tom van Rooij)

Figure 8.7 Citizen Science encourages broad participation of non-experts in science and engineering. Left: UpStream is a project that uses ambient displays to raise awareness about water consumption and promote conservation in public and private spaces [Kuznetsov and Paulos 2010b]. Middle: MyPart is a wearable, personal particle sensor that allows users to track and visualize air pollution [Tian et al. 2016]. Right: A sensor package mounted onto a street sweeper, transforming it into research vehicle for monitoring air quality and analyzing the environmental action landscape [Aoki et al. 2009].

people's environments. They bring their scientific research, design, and art into society to encourage broad participation by non-experts within science and engineering, and invites them to improve their environment, human health and well-being (shown in Figure 8.7). Paulos' Citizen Science project (2006-2015) focused on crowd-sourced data around public health and well-being, and invited people to create new connections with their own environment. For example, his projects include the collection and visualization of air quality data from Accra, Ghana by students and taxicab drivers [Paulos et al. 2008]; deployment of air quality sensors onto San Francisco municipal street sweepers [Aoki et al. 2009]; and persuasive displays for water conservation in public, private, and semi-public contexts [Kuznetsov and Paulos 2010a].

Such TEI approaches support collaboration among various stakeholders through multiple access points in different contexts, by using different kinds of tangible and embodied interaction, and by facilitating exploration and experimentation with different objects, visualizations and simulations.

We highlighted here only a small number of TEI system for collaborative placemaking and building sustainable communities. Many more examples can be found that focus on the environmental and social fabric of inclusive and sustainable communities. By bringing together community members, policy makers, and experts, TEI systems could facilitate participatory co-design of solutions that broaden participation in planning and placemaking, and result in more inclusive communities that are inclusive, safe, resilient and sustainable.

Agenda for TEI Design and Deployment

- Design and develop tangible and embodied ways of interaction that support collaborative placemaking through the manipulation of tangible media. In particular, focus on developing interfaces that are scalable, affordable, and accessible for diverse communities, preferably used in their own context.
- Develop tools and approaches that enable people from various backgrounds, disciplines, cultures, age, etc. to communicate and explore their challenges and opportunities together. Technology might support this interaction, but should never be a hindrance or barrier for people to engage, such as when they are tech illiterate.
- Develop tools that invite and facilitate collaboration between all the different stakeholders, from placemaking, architectural and urban planning professionals, to policymakers and civil servants, to community members and all other stakeholders that are involved. Utilize tangible and embodied interaction to facilitate interactive and participatory sessions where participants can easily express, experience, and explore ideas together.

Agenda for TEI Research

- Invent new expressive tangible media that could be manipulated (both programmatically and manually) to simulate a wide range of materials, processes, and phenomena.
- Design novel interaction techniques that enable users with different abilities and backgrounds to engage in collaborative placemaking, planning and building sustainable communities.
- Explore the possibilities and impact of different scales (full size and small-scale models) and perspectives (first-, second-, and third-person perspectives) of visualization, simulation and interaction.
- Study the impact of technology-mediated collaborative placemaking on the quality of solutions explored and adopted, and on long term acceptance of those solutions.
- Go beyond the physical and technological aspects of placemaking and planning, and also research the social dynamics and long-term dimensions of communities and places.

Lifelong inclusive learning for all

When one says 'education and learning,' the majority of people think of classrooms and institutionalized learning. In more classical educational approaches, education is often centered around the teacher, who determines what all students should learn, and how to operationalized the material so that it can be taught in uniform lessons and tested in objective and predictive ways [Hummels 2017]. New educational paradigms, however, are centered around the student and offer a variety of approaches, procedures and assessments, depending on the individual learner and the context [Doll Jr 1986]. Ken Robinson [Robinson 2010], an international education advisor and art education expert, explains it as follows:

"I think we have to change metaphors. We have to go from what is essentially an industrial model of education, a manufacturing model, which is based on linearity and conformity and batching people. We have to move to a model that is based more on principles of agriculture. We have to recognize that human flourishing is not a mechanical process; it's an organic process. And you cannot predict the outcome of human development. All you can do, like a farmer, is create the conditions under which they will begin to flourish."

The TEI community has for many years explored these conditions by developing new tools for classrooms [Bakker 2013b; Verhaegh et al. 2013], for learning abstract concepts from subjects such as math and programming in a hands-on way [Andersen and Ward 2017; Girouard et al. 2007; Horn and Bers 2019; Horn and Jacob 2007c; Mickelson and Ju 2011], for supporting full-body, multimodal and augmented ways of learning [Ahmet et al. 2011; Bakker et al. 2011; Damala et al. 2016; Holland et al. 2009; Malinverni et al. 2016; Price and Jewitt 2013; Radu and Antle 2016; Roberts 2015], for learning about nature [Mann 2012], for augmenting learning for children with special needs [Grönvall et al. 2006; Hengeveld et al. 2013b; Quek and Oliveira 2013] and for teaching at-risk populations [Antle et al. 2018].

The latter TEI tools address societal challenges such as accessibility and inclusiveness. While acknowledging the major progress that has been accomplished towards increasing access to education around the world, and in particular the growing enrolment of women and girls to schools, the UN sustainable development goals call for "bolder efforts [that] are needed to make even greater strides for achieving universal education goals" [Nations]. We believe that TEI researchers and practitioners could make important contributions to these efforts by fostering learning in diverse populations across all levels of education.

In Chapter 2 we described the in-the-wild application of TEI tools for learning across a variety of content domains, then in Chapter 4 we discussed the cognitive foundations for supporting learning with TEI. In this chapter, we highlight projects that focus on providing quality education to children from at-risk populations.

The Mind-Full project [Antle et al. 2018] aims to help children from at-risk populations who suffer from trauma and anxiety, to stay calm and focus on learning. To help children learn how to self-regulate anxiety and attention, the researchers have developed a brain-tablet application that engages children in the practice of meditation using neurofeedback, making invisible brain processes understandable for children.

The project started in Pokhara, Nepal, where a development team, consisting of senior HCI researcher Alissa Antle and trauma therapist Leslie Chesick, worked closely with the NGO Nepal House Society Kaski, which funded and operated a school for young girls living in poverty. While the girls attended the school, many of them had difficulty learning due to multiple traumas and anxiety. To address this problem, the team designed and built a brain-tablet game application so that the young students, who were often illiterate, could improve their self-regulation of anxiety and attention. The application includes three games (shown in Figure 8.8, each with a culturally-relevant activity familiar to the children from their everyday lives. Two of the games were designed for relaxation and one for sustained attention. The games' input is the children's brain wave activity, measured by the commercially-available NeuroSky headset. The application also includes a module for calibration (shown in Figure 8.8, which runs on a separate tablet and allows an adult to monitor the children's brain activity values.

A field trial using the application in Pokhara school showed that children were able to acquire self-regulation skills and transfer those skills into their learning and play activities. Positive effects were maintained for two months post-intervention. Based on these promising results, the team refined and extended Mind-Full by building three new versions (shown in Figure 8.8), Mind-Full Wind (Nepal), Mind-Full Wild (Urban), and Mind-Full Sky (Aboriginal)). They released beta versions of the new Mind-Full apps on the Google Play store and conducted additional field studies with children living with trauma in an urban environment in Canada. They found similar results that indicated positive impact and evidence of improvement on objective measures.

A different population of at-risk learners include children with dyslexia or other learning disabilities. Several TEI projects seek to help such children to acquire reading and language skills. For example, the PhonoBlocks system [Fan et al. 2017a] (shown in Figure 8.9), by Antle and her team, consists of tangible letters encoded with visual or haptic information. The research team has developed dynamic color and haptic coding strategies to enable reliable two-dimensional decoding, enforce correct letter orientation, and enable epistemic strategies that simplify spelling tasks. The system was designed for and evaluated with 7 to 8-year-old children at risk for dyslexia. Results from a field study show promising results, indicating significant gains in reading and spelling.

The LinguaBytes system [Hengeveld et al. 2013b] (shown in Figure 8.10), developed by Hengeveld and colleagues, aims to stimulate language development for non-verbal or hardly-speaking toddlers. The system consists of a digital display, a physical control panel, and a range of playful tangible input materials including story booklets and 3D tangible input figures. Using the materials, children can read interactive stories and engage with a variety of linguistic exercises together with an adult and with other children. Evaluating the system demonstrated

Figure 8.8 The Mind-Full project created to support at-risk children to learn and practice self-regulation of anxiety and attention; (a) shows real-time calibration and personalization of the application by a parent, teacher of counselor; (b) shows the original games used in Nepal; and (c) shows two variations developed for Indigenous and for multi-cultural Canadian children. Illustration Credit: Rachael Eckersley 2017.Photo Credit: Elgin Skye McLaren 2018. [Antle et al. 2018].

that the tangible interaction provided opportunities for collaboration between a child and a therapist, and showed increased engagement, thus offering more opportunities for learning. Most importantly, the various materials and ways of interaction were designed based on low-threshold physical manipulation, thus allowing children with motor disabilities to do similar things as "normal" children, helping them to raise their self-esteem and confidence.

TEI demonstrates the benefits for different populations of learners. This applies beyond children from at-risk populations. Hummels [2017] discerns ten parameters that can be useful for exploring the boundaries of designing TEI for lifelong inclusive learning for all. Every

Figure 8.9 PhonoBlocks, a tangible system designed to help dyslexic children build reading and spelling skills. In the image shown, the color of the A letter changes from yellow to red, signaling that the vowel sound has changed from short to long when the trailing E letter is added.Photo credit: Min Fan 2017. [Fan et al. 2017a].

Figure 8.10 The LinguaBytes system, created for developing verbal skills in children. Clockwise from top left: the output module for displaying interactive content, the base module, the story module, the exercise module, cards, input figures, story booklets, and the control module [Hengeveld et al. 2013b].

parameter revolves around two or three non-mutually-exclusive opposites. Moreover, new opportunities can be created by combining different parameters:

- Self-Directed vs. Directed Learning
- Competency-Centered vs. Knowledge-Oriented Learning
- Perceiving and Doing vs. Making vs. Thinking
- Formal vs. Informal Learning

- Learning at an Institute vs. Learning in Society
- Learning during Dedicated Time Slots vs. 24/7 Learning
- Life-Long Learning vs. Learning at School
- Offline vs. Online (Digital) Learning
- Learning Alone vs. in a Uniform Group vs. in a Diverse Group
- Reflection vs. Ongoing Action

We identify the following agenda toward TEI support for inclusive and quality education:

Agenda for TEI Design and Deployment

- Partner with NGOs and community organizations to reach and understand the context, needs, and intricacies of underserved learner populations around the world.
- Collaborate with learning specialists to create TEI systems that are developmentally appropriate for learners with different abilities and draw upon familiar concepts and materials to help people learn new skills.
- Develop TEI solutions that are affordable, scalable, and robust.

Agenda for TEI Research

- Investigate how to leverage embodiment, tangibility, materiality, and multisensory interactions to enhance the learning process and outcomes of learners with different abilities, different ages and skills, and within various contexts.
- Consider the ethical issues of conducting research with vulnerable populations. Antle identified five ethical questions for researchers to answer [Antle 2017] that examine the potential benefits and possible harms for the vulnerable populations involved, as well as issues of consent and expectation management.
- Realize that testing prototypes with vulnerable user groups in the wild creates expectations. Ethically, you cannot simply stop after the tests and experiment are done and expect the users to go back to their current ways of learning. Be aware of the impact of your research and preferably create ways to continue offering the prototypes, even after the research is done.
- Think beyond the specific learning tool to consider learning ecosystems, which include all relevant aspects, stakeholders, context etc. in the design.

Professor Alissa N. Antle, Simon Fraser University, Canada
Looking Ethically Forward: Shaping the Future of Smart Wearables for Children

In the Global North and increasingly in the Global South, today's children connect, communicate, create, learn and recreate using devices that have moved from classrooms to bedrooms to backpacks to wrists and heads with breathtaking speed. These devices currently collect, store and transmit data about children including their location, physical activity levels, text conversations, photographs, app usage and more. The next generation of these devices includes: smartwatches, augmented glasses, wearable EEG (electroencephalogram) headsets, digital tattoos, and biosensing patches. By 2022, sales of smart wearables are expected to double; reaching a $27 billion+ market with sales predicted at over 223 million devices [Lamkin 2018]. This next generation of wearable devices have the ability to collect bio-data about a child's body including: heart rate, breathing rate, galvanic skin response, electrolyte concentration, blood sugar levels. Wearable headsets will collect data about children's brains including neural patterns and activity levels in different frequencies and regions. EEG headsets can already indicate the wearer's level of attention, stress, auditory processing, or cognitive load as well as reveal to some extent the wearer's emotions, memories and perceptions.

In the near future, smart wearables will exponentially increase the number and nature of biodata streams available to and about children. This biodata will be used as input for apps designed to improve children's learning, productivity, and well-being, to diagnose and access them, and in all likelihood for myriad other purposes we have yet to imagine. Proponents of *lifelogging*, also known as the *quantification of self* movement, claim these technological advances will enable people, including children, to improve their physical, mental, and emotional performance. I wonder how this unitary focus on performance may impact children. More importantly, how else might these technologies impact children? When we look beyond performance to social and emotional development and well-being, it is evident that there will be other impacts, some positive, and some less so. For example, these technologies will impact children throughout their childhood as they formulate their identities and build relationships with peers and parents. They will impact children's sense of agency and may steer their development of empathy and social skills. And like the Internet, these technologies will most certainly change who children turn to for epistemic authority – for knowledge about themselves and their peers.

What is needed, now, before these technologies become mainstream, is consideration of the following question: In what ways might the quantification of self through smart wearables and other biosensing devices impact children – both positively and negatively? And following from those answers we must ask: What guidance can we provide to technology researchers, industry developers and educators that will help steer this new wave of technology design towards a comprehensive and nuanced positive computing agenda [Rodriguez 2015]? It is imperative that we ask these questions now, while we are researching, designing and developing these technologies, so that we can shape rather than retrospectively react to the impacts these emerging technologies will most certainly have on children's lives for many generations to come.

Alissa Antle is a Professor at the School of Interactive Arts & Technology at Simon Fraser University. Her research focuses on ethical studies of child-computer interaction, and interaction design for children. She designs and builds interactive technologies, with an emphasis in exploring how these technologies can aid and augment children's emotional and cognitive development. Her interests also include sustainability and social justice, and critical ethics of working with vulnerable populations. She has been acknowledged as one of Canada's intellectual leaders after her induction to the Royal Society of Canada's College of New Scholars, Artists and Scientists in 2015.

Synergies across scientific, technical, and art+design (STEAM)

In his book, Tools for Thought [Rheingold 2000], published originally in 1985, Howard Rheingold examines the work of innovators who "shared a vision of personal computing in which computers would be used to enhance the most creative aspects of human intelligence – for everybody." In the decades following, personal computing, the development of graphical interfaces, increasing internet connectivity, and the wide adoption of the web, have seen tremendous progress, bringing radical change to the way individuals explore, learn, create, play and work. These developments have also provided new means for communities of various scales to form and collaborate across space and time, thereby fostering discovery and creativity. However, the quest for augmenting people's cognition and their ability to work creatively and collaboratively is ongoing.

We believe that advances in TEI afford new opportunities to further augment human perception and cognition, and foster creative exploration, design, and discovery. We view developments in STEAM (science, technology, engineering, art, and math) and TEI as intertwined and prospectively advanced by leveraging old and new synergisms between scientific disciplines, arts, and culture [Ullmer 2012c]. Here, we highlight areas in which TEI intersects with and advances through new interfaces across the arts and sciences (STEAM).

Novel approaches, methods and tools for innovation

Gardien et al. [2014] argue that "if a company continues to use processes, methods, tools and competencies from an older paradigm, it can only come to solutions that fit that older paradigm." Moving towards new paradigms such as the transformation or purpose economy as explained above, require us to develop new approaches and means for innovation. When looking at the transformation economy as described by Brand and Rocchi [2011]; Rocchi

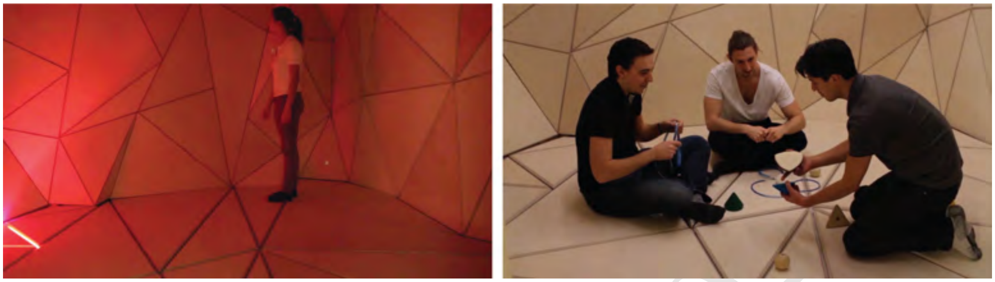


Figure 8.11 The Blue Studio, a creation space in which people can work together on ideation processes through exploration and bodily engagement [Jaasma et al. 2017b].

et al. [2018], people are looking for methods, tools, products, systems, and services to help them to move towards a sustainable world. Since sustainability is a complex issue and requires a systemic approach, the collective becomes as important as the individual, meaning that stakeholders will increasingly work together on local solutions for local issues that stem from greater global issues. So, how can TEI facilitate such multi-stakeholder, interdisciplinary collaborations that are based on engagement, empathy and respect for each other's perspectives and expertise; where all stakeholders are equal, but not identical, and valuable in their own way? How can TEI enable participants to have an open attitude, where they put their point of view, their value system, their experience and their skills into the shared design space [Hummels and Lévy 2013]?

The Blue Studio [Jaasma et al. 2017b] (shown in Figure 8.11) is an example of an interactive creative space for embodied multi-stakeholder ideation processes within innovation projects. It is a part of Sliperiet, a research and innovation center at Umeå Arts Campus at Umeå University, Sweden, which is also occupied by and accessible to companies and other external stakeholders. The studio is developed for creative empowerment by offering a physical ideation space enhanced with digital services. Based on input of sensors, the space triggers exploration and bodily engagement through elements such as light, sound, physical surfaces, and tools. The space includes a tablet with an automated filming app that records 1-minute movies of the scenarios that the participants create. For people not familiar with design, as many stakeholder consortia of specific societal challenges are, the room guides the group through an entire design process, and emails the video outcome to the participants after the session.

Within the Blue Studio, the participants can also make use of the Embodied Ideation Toolkit [Hummels 2016; Smit et al. 2016] (shown in Figure 8.12). This is an embodied design tool existing of several interconnectable objects, including the room itself, to support co-design processes by enabling participants to act out scenarios, create new design concepts, and/or visualize patterns and relationships. This toolkit can be used in various settings.

Figure 8.12 The Embodied Ideation Toolkit, with many different objects that can be connected together magnetically, can be used to boost creativity by enabling the creation of scenarios and visualizations of relationships [Hummels 2016].

In the world of art, new tools and installations have been developed to create multiple collaborative perspectives based on engagement, empathy and respect for each other's perspective and expertise. Several artists' creations enable people to experience the perspectives of another's body. Although full-body swapping appears to be quite a long way from becoming reality, one can find various experiments and prototypes that give people the experience of taking in the perspective of another person [Mitchell et al. 2017c]. For example, in "Parallel Eyes" [Kasahara et al. 2016b] (shown in Web Companion 8.1). people can see shared first-person perspective videos from three other people next to their own view. Similarly, the Channel Surfers [Sypniewski et al.] explore a similar approach by experimenting with constant rapid switching between second- and third-person live camera perspectives. Another prototype, Biosync (Web companion 8.1) uses electrical stimulation instead of vision to synchronize muscular activity, enabling for example healthy people to experience the tremors a Parkinson's disease patient normally experiences [Nishida and Suzuki 2016b]. Hsincheng Hou et al. Hou et al. [2017b] even developed a game called "Human and Dog," in which a human avatar and a dog avatar communicate to solve a series of puzzles, giving another perspective of the world through unequal communication capabilities.

Web companion 8.1 (pathsForward/figs/a1)

Parallel Eyes [Kasahara et al. 2016b]; Middle: The Channel Surfers [Mitchell et al. 2017b]; Right: BioSync [Nishida and Suzuki 2016b].

Agenda for TEI Design and Deployment

- Design and develop tools based on embodied interaction that enable stakeholders from various backgrounds, cultures, ages, and disciplines to collaborate in an equal, empathic and respectful way where ideas can be expressed, experienced, and explored.

- Make these tools affordable and easily accessible to be used in context.
- Practice what you preach: develop tools in participatory processes, with a variety of stakeholders.

Agenda for TEI Research

- Research the concept of first-, second- and third-person perspectives (e.g. [Smeenk et al. 2016] and [Svanæs 2013]) and implement and study the consequences for TEI.
- Explore the concept of alternative perspectives (e,g. of animals) to get a different perspective on today's challenges and potential opportunities to develop new solutions.
- Research the societal impact of using embodied tools in everyday multi-stakeholder design and innovation processes.
- Explore the possibilities of embodied interactions in other disciplines and realms dealing with societal challenges such as governance, economics and change management.

Complex systems

Our societal challenges push us towards finding solutions on a systemic level. The World Economic Forum argues that we need interdisciplinary collaboration to understand and tackle the underlying principles of the complexity in our world in order to face our societal challenges like poverty and climate change [Barabasi et al. 2013]. It requires a new kind of science [Ball 2012] where scientists from different disciplines can address the core of complex systems, including emergent collective behavior, transitions between system states, and resilient complex systems that can handle external shocks or disruptions [Vermeer 2014]. The interconnectivity of our global value chains, our communication systems, and other technologies can present challenges, but it also provides an opportunity for new and successful societal interventions.

Up until now, TEI has only scratched the surface of exploring and applying the characteristics of complex systems, such as open-ended self-organization, nonlinearity, and adaptivity [Braley et al. 2018a; Dietz et al. 2017; Suzuki et al. 2019].

There is a huge potential for TEI within the realm of complexity science, which encompasses for example, cybernetics, systems theory, dynamical systems, nonlinear systems, chaos theory, social networks, artificial intelligence, game theory, neural net, synergetics, artificial life [Vermeer 2014]. TEI can help make complexity graspable, but can also help to intervene in society through its designs and to explore emergent behavior of people and communities. For example, can TEI influence passengers' behavior in situations such as transportation delays? Can TEI propose forms of automobile interactions that lower traffic jams? Can TEI reduce chaos and panic in large crowds due to unexpected events? Can TEI support social cohesion and invite citizens to work together on societal challenges? These larger complex challenges will require new modes of interaction and new technology within interdisciplinary areas that are unfamiliar to TEI. In the next section (6.3), we will address at least one those directions: TEI and biology.

Agenda for TEI Design and Deployment

- Work with people from other disciplines to develop tangible and embodied tools that can support analyzing and visualizing complex systems.
- Develop emerging tangible and embodied tools and systems that can catalyze transitions in communities, such as innovation in a social system.

Agenda for TEI Research

- How can TEI contribute to complexity sciences and develop new embodied propositions and hypotheses that can study complex phenomena?

Associate Professor Ambra Trotto, Umeå Institute of Design, Sweden
Senior Design Researcher Jeroen Peeters, RISE Prototyping Societies in Umeå, Sweden
Complexity, Responsibility, Collaboration and Material Consciousness

What the French Revolution has taught us, is that in order for a new civilization to emerge, you need to establish new practices. From those practices, a new way of thinking can flourish.

The unprecedented challenges that we face nowadays, together with the speed of technological advancement, demand a new civilization. The skills that such civilization needs to have are not completely apparent yet. However, some of them have clearly emerged in the last decade.

One is clearly the ability to withstand and **navigate contemporary complexities**; challenges that are difficult to frame, that escape linear laws of causality. The problem-solving attitude, legacy of the Industrial Revolution, does not work in a connected world. Societal challenges emerge as global, they require systemic approaches to be understood and tackled. And the tackling, to be meaningful, needs to be situated in specific contexts.

This leads to the necessity of a new, more elaborate and mature **sense of responsibility**, since it is becoming so clear how local actions have global repercussions. It has become clear how the ethically blind implementation of more or less intelligent digital technologies in all aspects of our life has ruthless consequences. This sense of responsibility can be trained in the form of ability to question, forecast, simulate and prototype what transformations are triggered by our actions.

Connectedness and the potential magnitude of our actions' repercussions, as well as the complexity of new challenges, require the integration of many different points of view: they require **collaboration**. People from different backgrounds, with different agendas, different professional practices, different competences and skills, different ways of thinking and acting are now requested to collaborate. Having been professionally educated in a world that had different driving values, such as maximizing efficiency, striving for standardization, sectorialising competences, promoting linear processes and top-down decision making, we find ourselves unprepared for collaborating across all scales of diversity.

Another skill that our times require, is a **renewed material consciousness**, which has become necessary with the spreading of digital technologies. This, among all aspects listed above, is the one that the TEI community has mostly dealt with. Researchers of the TEI community have, for instance, looked into ways of sketching with the digital, highlighting the relevance of an embodied way of relating to such technologies, to create meaningful interaction possibilities. This new civilization needs transformative practices

[Hummels et al. 2019], which promote and support all the elements that have been sketched above and search for new elements that have not emerged yet. New environments that promote transformative practices are necessary.

In Umeå, Sweden, we are prototyping and piloting the Pink Initiative at Scharinska Villan, a process applied to a place, where embodied practices of collaboration across cultures, agendas, disciplines are developed. Both the public (the Region and the Municipality, as well as municipality-owned companies) and the private sector meet in this neutral place, curated by the Swedish Research Institute (RISE). This is a place that affords Making, through workshops, tools and facilities. Such encounters are designed and orchestrated to professionally educate participants towards practices of transformation. This Initiative will then be replicated in different instances and situated in different national and international contexts.

Having stemmed from a more techno-centric perspective, the work done at TEI has moved, informed, proposed instances and created knowledge around the notion of embodiment. The other skills that our times require, i.e., boosting the ability of cross-collaboration, evolving skills related to ethical questioning and promotion of social responsibility, as well as the ability to navigate complexities, constitute a possible reference for what this community can pay attention in the future.

Authors draw upon the following texts: [d'Alembert and Diderot 1751; Flores 2008; Frens et al. 2003; Hunt 2007; Huxley and Hitchens 2005; Kant et al. 1994; Merleau-Ponty 1945a; Sennett 2009; **?**].

Ambra Trotto is associate professor at Umeå Institute of Design. At RISE, Research Institute of Sweden, she is director of the Pink Initiative, establishing transformative ecosystems that elicit systemic change towards socially and environmentally sustainable futures. At RISE, she also leads the area of Digital Ethics and contributes to the development of the area Value-shaping System Design.

Jeroen Peeters is a Senior Design Researcher at RISE Prototyping Societies in Umeå, Sweden. Jeroen works with the public and private sector to develop and experienceable proposals for societal transformation based on design research methodologies. RISE stands for Research Institutes of Sweden - the national polytechnical research institute owned by the Swedish state. .Jeroen holds a PhD from Umeå, University and has a background as an Industrial Designer, trained at Eindhoven University of Technology.

New Interfaces Between Biology and TEI

Advances in life science technologies have transformed biological inquiry and have the potential to alter medicine to offer much-improved health care [Chin et al. 2011]. Biological technologies are also positioned to address pressing challenges, including food and clean water shortages, and increased demand for alternative energy sources [Carlson 2010]. In addition, biological materials provide new opportunities for creative and artistic explorations [Pataranutaporn et al. 2018]. These developments have opened new interfaces between biology and TEI, motivating researchers and designers to explore and envision new ways for people to interact with biological data and systems. In Chapter 2, we highlighted TEI systems and approaches that foster learning in Biology. Here, we discuss TEI work focusing on modeling and visualizing biological data sets, and designing and constructing with biological elements.

Modeling and visualizing biological data sets

Based on our own experiences working at the intersection of biology and TEI both as interaction designers [Konkel et al. 2020; Shaer et al. 2010, 2011, 2012; Ullmer 2012c; Wu et al. 2011] and genomic investigators [Han et al. 2007; Locke et al. 2011; Sequencing et al. 2007], we propose that TEI offers unique opportunities for enhancing discovery, exploration and learning of biological data. Three systems that demonstrate TEI approaches for supporting complex data and model exploration include: G-nome Surfer, Active Pathways, and Eugenie.

G-nome Surfer [Shaer et al. 2010, 2011, 2012] (see Figure 8.13) is a tabletop interface for browsing prokaryotic genomic data, designed to support teams of students participating in authentic scientific inquiries. Its design was motivated by the lack of bioinformatics tools that could support integrated workflow while facilitating collaboration, learning, and high-level reasoning [Bolchini et al. 2008; Mirel 2009]. The system utilizes multitouch interaction techniques with a visual genomic map. Users are able to explore genomic sequences through both coarse and fine navigation, while maintaining a sense of location. In addition, users can spatially manipulate, annotate, and compare heterogeneous information artifacts. Beyond genome browsing, the system supports manipulating DNA through primer design, which involves the identification and testing of short sequences of DNA that mark the start and end of a particular region of DNA sequence. G-nome Surfer was deployed in lab settings and evaluated with undergraduate student researchers. Findings indicated that G-nome Surfer was effective in fostering collaborative exploration of large amounts of genomic data. As genomic data becomes increasingly available to general audiences through direct-to-consumer genetic testing, there is a need to consider and design new interfaces that will support non-experts in curating and making sense of their own data [Shaer et al. 2017].

In Chapter 4, we described Active Pathways [Mehta et al. 2016b] (see Figure 8.14), a system that combines active tangibles and a tabletop system to support collaborative discovery and learning of biochemical reaction networks through building external models. The interaction flow is defined around the two major tasks involved in modeling bio- chemical pathways: building the model, and fitting the model to experimental data by adjusting parameters. Multiple active tangibles are used both on and off the tabletop for model construction and fitting tasks. Grouping the building and fitting functions creates an agile environment wherein users can quickly build, modify, and test their pathways iteratively without having to switch context. One can switch between the options inside each of these categories by tilting the cube,

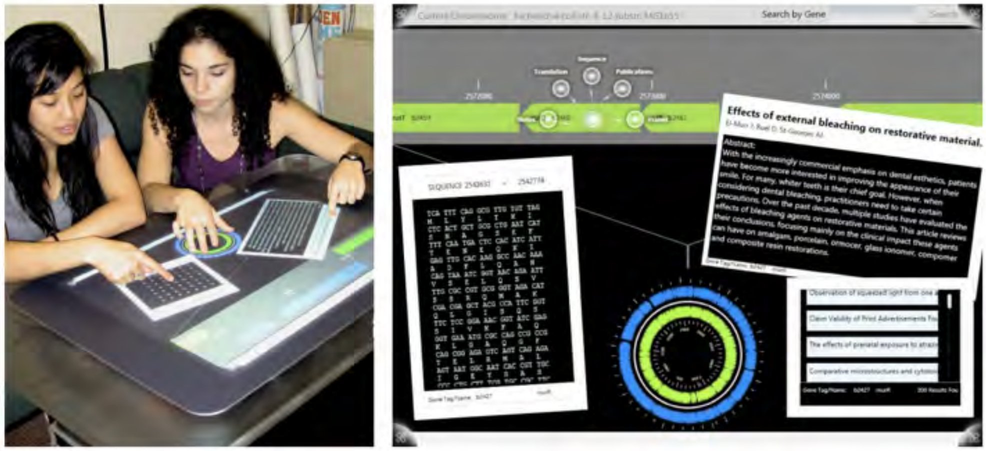


Figure 8.13 Students using G-nome Surfer Pro (left): displaying chromosome visualizations, DNA sequence, and related publications (right) [Shaer et al. 2013].

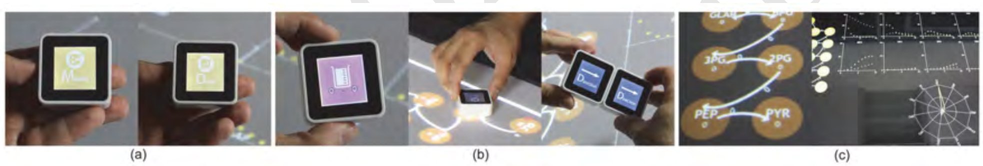


Figure 8.14 Active Pathways' top-level menus on the active tangibles. (b) Model creation with active tangibles. Here, the user first selects the "Concentration" option from the menu on the tangible, places it on a molecule on the table, and then uses it like a dial to adjust the concentration parameter. S/he can also create a reaction by touching two molecules together and tilting to set the direction. (c) Data visualization in Active Pathways. The directional graph visualization represents the pathway, while the radial chart and scatter plot visualizations are for comparing model and experimental data [Mehta et al. 2016b].

including creating and modifying molecules, enzymes, and reactions. Results from evaluating the system with novice researchers indicate that it can facilitate an understanding of complex systems and collaboration.

Similar to Active Pathways, Eugenie [Grote et al. 2015] (see Figure 8.15), is a TEI system which utilizes active tangibles to help synthetic biologists with the intricate and data-driven workflow of bio-design. The system combines tangible active tokens with physical constraints to provide users with persistent and integrated representations of data and with physical constraints to enforce interaction syntax. Using the system, synthetic biologists can explore the

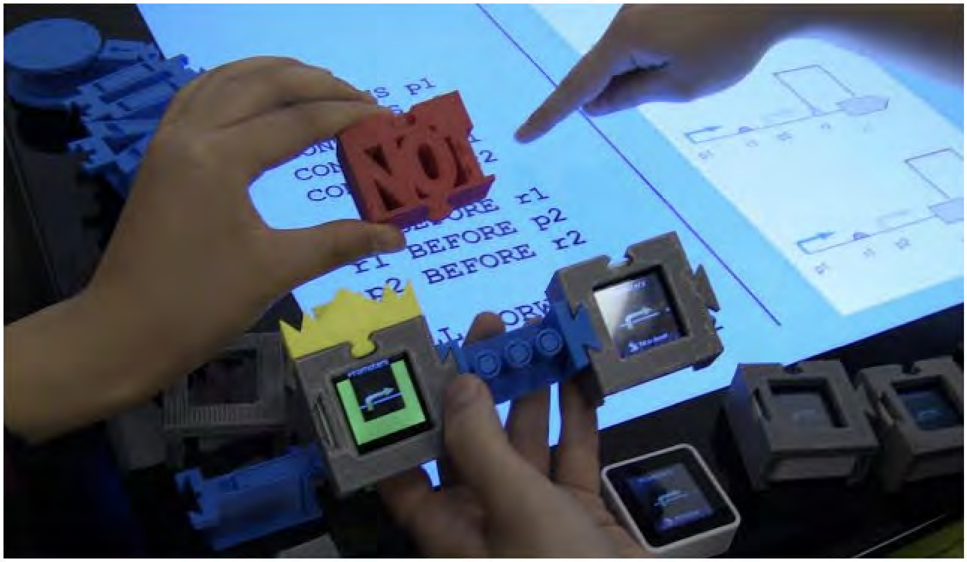


Figure 8.15 Two users interact with Eugenie, constructing bio design rules using tangible tokens. Upon "stamping" a rule on the surface, a new Eugene statement is added to the rules panel [Grote et al. 2015].

design space of particular biological constructs. Active tokens represent generic or concrete biological parts that are dynamically associated by the user. Passive tokens, on the other hand, are statically bound and represent various query operators. Users specify structure rules by connecting active and passive tokens. Users then “stamp” the physical structure on a tabletop to embody the transferal of data from the pieces in the user’s hand to the surface. Upon stamping, the physical representation of the rule is transformed into a digital representation and the rule is applied to the design of the biological construct.

These three systems highlight opportunities and challenges for TEI to enhance learning and discovery with large datasets:

- Facilitating thinking through action. All three interfaces draw upon the cognitive foundations discussed in Chapter 4, to apply various strategies for reducing cognitive workload including sorting and arranging artifacts, gesturing with and around tangibles, and combining epistemic and pragmatic actions.
- Achieving scalability through the use of active tokens and dynamic binding. One of the core limitations of tangible user interfaces is scalability [Shaer and Hornecker 2010b]. Providing tangible representations for large data sets might require a large number of

tangibles that take up space and are difficult to manage. However, active tokens enable users to interact with large data sets using a compact set of tangibles.

- Utilizing new interaction spaces. Active tokens can be manipulated independently of physical constraints through gestures. Designing for interactions beyond a surface help to overcome challenges common to data-intensive applications.
- Enforcing interaction syntax with physical syntax. Constructing complex queries often requires abiding to strict syntax. Physical constraints afford certain actions while preventing (or increasing the threshold for) others.
- Supporting and fostering effective collaboration by using large interactive displays, multiple access points, spatial arrangements, and exchange of physical objects.

Designing and constructing with biological elements

A different interface between biology and TEI involves designing materials, objects, and structures that are inspired by and constructed with biological elements. Advances in biology and materials science provide designers with access to novel tools for manipulating biological elements in different scales – from the micro scale of molecules and cells, to the architectural scale of buildings. Leveraging biological processes such as mutation, reproduction, and self-assembly, an emerging body of work explores new symbiosis between living organisms, our own bodies, and physical objects [Pataranutaporn et al. 2018].

Here, we describe three case studies:

Trap it! [Lee et al. 2015] (shown in Figure 8.16) is a museum exhibit that allows visitors to interact with living cells. The exhibit consists of a touchscreen, interactive microscope, and light projection. Visitors draw patterns on a touchscreen over a magnified real-time view of photoresponsive microorganisms. The drawings are projected onto these microorganisms as light beams, which are sensed by the cells and cause the microorganisms to change their swimming motion.

bioLogic [Yao et al. 2015b] (shown in Figure 8.17) is a project led by the Tangible Media Group at MIT Media Lab in collaboration with MIT Dept. of Chemical Engineering, Royal College of Art and New Balance, which investigates the use of bacterial cells as living sensors and actuators. The team produced bio-hybrid film from natto cells, which expand and contract relative to changes in the atmospheric moisture. This film is assembled by a micron-resolution bio-printing system and transformed into responsive fashion, a “Second Skin,” which reacts to body heat and sweat, causing flaps around heat zones to open and cool down the body. The bio-hybrid film can also be utilized in other contexts, such as bio-hybrid flowers, which blossom with both shape and color changes, or living tea leaves that signal when the tea is ready through shape transformation.

The Silk Pavilion [Oxman et al. 2014] (see Web Companion 8.2) is an architectural scale project installed at the MIT Media Lab created by Neri Oxman and her team from the Mediated

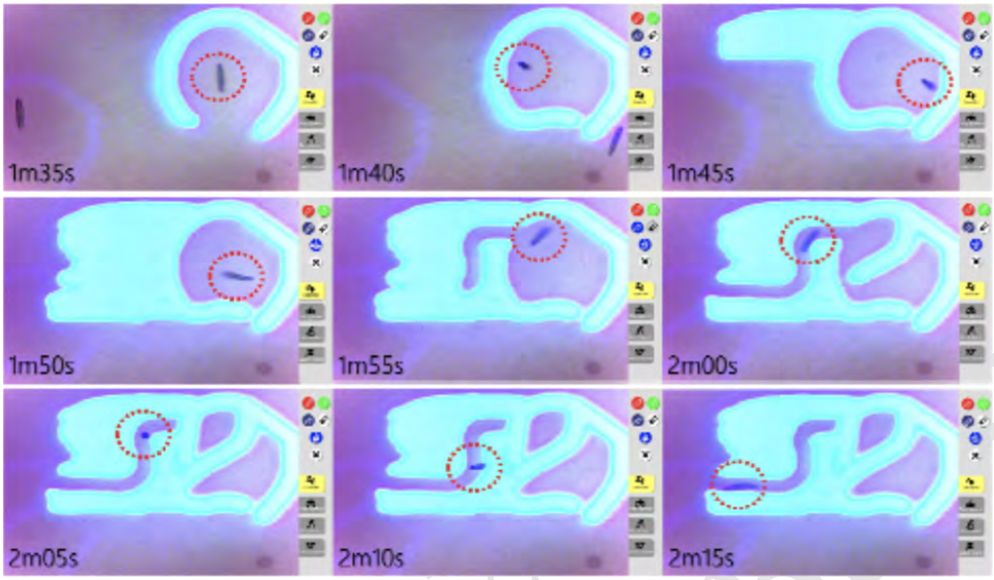


Figure 8.16 The Trap it! interface allows users to draw on a touchscreen that displays a microscope view of *Euglena gracilis*, a photoresponsive microorganism commonly found in ponds. The user can interact with the cells by adding to or erasing from their creation which is projected real-time onto the cells. Known to be photophobic to blue light, these cells change their movement to avoid the drawing [Lee et al. 2015].

Matter group. The project explores how digital and biological fabrication techniques can be combined to produce architectural structures. The pavilion consists of a primary structure consisting of polygonal panels made of silk threads laid down by a robotic arm, which was programmed based on the way a silkworm deposits silk to build a cocoon. The panels were arranged to form a suspended dome, on which 6500 live silkworms were placed so that while crawling over the dome they deposit silk fibers and complete the structure. Researchers from the University of Tsukuba [Iwasaki et al. 2017], extended the methods introduced in the Silk Pavilion to develop new methods of constructing arbitrary small three-dimensional silk sheets using silkworms.

Figure 8.17 bioLogic, fabric that reacts to body heat and sweat. Image courtesy MIT Media Lab.

Web companion 8.2 (pathsForward/figs/a2)

The Silk Pavilion, a combination of fabricated and natural silk [Photo by Neri Oxman - Mediated Matter Group, CC BY-SA 4.0[a]].

[a] https://commons.wikimedia.org/w/index.php?curid=50361306

Taken together, these examples introduce new and exciting opportunities for advancing TEI through the creation of novel systems and materials that are inspired by and constructed with biological elements. We envision increasing use of interactive materials that are "grown" rather than manufactured, leading to widespread adoption of sustainable materials and practices for TEI.

Agenda for TEI Design and Deployment

- Collaborate with scientists to develop tangible and embodied tools that support and enhance discovery with large heterogeneous data sets.
- Create developmentally appropriate and accessible tangible and embodied interfaces that engage various audiences (ranging from children, to non-experts, to policy makers) with biological data sets and concepts.
- Develop affordable and accessible DIY tools that can be used safely and creatively by non-experts.
- Seek to create hybrid spaces that support hands-on biology work beyond the traditional laboratory settings. Establish spaces that bring together creative TEI practices and biological experimentation.
- Integrate familiar craft activities such as sketching, drawing, print making with microbiology protocols and wet laboratory work.
- Work in interdisciplinary teams to design materials, objects, and structures that are inspired by and constructed with biological elements.

Agenda for TEI Research

- What new interaction techniques and materials can bridge the time and size scales of biology to allow users to engage with biology in playful and meaningful ways outside the traditional wet laboratory?
- How to combine TEI approaches with biological elements to provide sustainable and accessible solutions to societal problems?
- What biological elements could be designed and used for creating TEI systems in various scale ranging from micro to macro?

TEI in the Age of Automation

In his column in Interactions Magazine, Uday Gajendar argues "we are living in an age of automation, where computational intelligence guided by algorithms in apps and sensors is woven into our daily lives" [Gajendar 2019], and highlights the importance of considering the implications of automation for the humans experiencing such artificial intelligence. We expect that while the involvement of computer-automated systems such as bots, cars, drones, and robots, in daily tasks will increase in the near future, rather than functioning in a fully autonomous manner, such systems will foster new forms of human-automation partnerships [Stone et al. 2016]. Such human-automation interactions could happen both when humans are co-located with machines (e.g. between a driver and their highly-automated vehicle) as well as virtually (e.g. between an operator and a robot deployed in a remote location). A challenge we face is therefore, to design human-automation interactions, which are intuitive, and promote safety, transparency, trust, productivity and wellbeing, as well as equity and dignity. Gajendar calls for such interactions to be shaped “with humanistic qualities, like emotion, conversation, and relationship” [Gajendar 2019].

Janssen et al. examined the history and current trends of human-automation interaction research through a literature review of work published during the last 50 years in the International Journal of Human-Computer Studies [Janssen et al. 2019]. They found that automated systems have been historically used more frequently in time-sensitive and safety-critical systems but that their use in embodied and situated systems, as well as by non-expert users is increasing. In their analysis, they discuss eight trends for future human-automation interaction research, distinguishing between themes that have been studied over the years (but continue to remain important), including: (1) function and task allocation between humans and automation, (2) trust, incorrect use, and confusion, and (3) focus, divided attention and attention management; and emerging topics such as (4) the need for interdisciplinary approaches and teams, (5) regulation and explainability of automation, (6) ethical and social dilemmas, (7) facilitating humane experiences, and (8) radically different human-automation interaction.

Considering the increasing use of automation among non-professional non-expert users and the integration of automation with embodied and situated systems, we anticipate that TEI will have an important role in addressing the challenges for creating intuitive, humanistic, and effective human-automation partnerships. TEI research on human-automation interaction is still in early stages, and we anticipate that the above themes will inform future work in this area.

Here, we highlight three exploratory projects that demonstrate the potential of applying TEI approaches to shaping novel forms of human-automation partnerships.

MetaArms [Saraiji et al. 2018], developed by a team of researchers from Keio University and the University of Tokyo, Japan, explores novel co-located collaboration between people and robotic body extensions (see Figure 8.18). The system consists of two wearable robotic arms and hands controlled by the user through feet motion - the arms are controlled by moving the feet, the robotic hands’ griping is controlled through toes bending. The system provides the user with haptic feedback presented on their feet, which correlates with the objects touched by the robotic hands. While the system is still is early exploratory phases, it introduces a new approach to control robotic limbs by remapping the user’s limbs onto the artificial robotic extensions, which opens a space for novel human-automation partnerships.

The Telesuit system [Cardenas et al. 2019b], demonstrates remote collaboration and control between a human operator and a telepresence robot - it is a full-body telepresence control system for operating a humanoid telepresence robot created by research from Kent State University, in the United States. The system consists of a head-mounted display (HMD), which projects real-time first-person video from the robot, and a full-body gender-neutral suit with motion-tracking and health monitoring sensors. The design of the garment carefully considered performance, functionality, and aesthetics. The locomotion of the robot and the grasping are

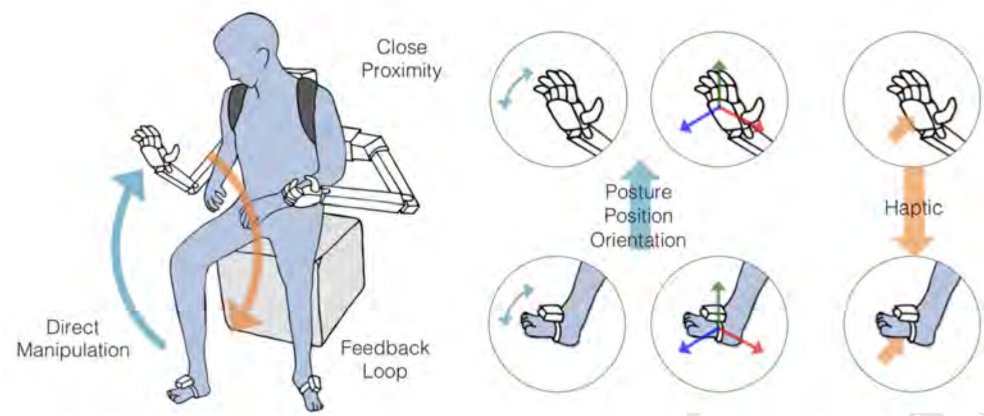


Figure 8.18 MetaArms allows a user to control a pair of robotic arms with their feet. The feet movement, tracked by sensors, maps to the robot that the user wears as a backpack [Saraiji et al. 2018].

controlled through force feedback using a VR joystick. Visual sensing is provided through a VR-HMD, and tactile feedback is provided using vibrating motors (shown in Figure 8.19). The motion tracking system integrated into the suit and used to control the robot's arms, waist and chest. The health-monitoring system allows the platform to leverage information such as respiratory effort, galvanic skin response, and heart rate, to adjust the telepresence experience and apply different control modalities that automate the robot manipulation tasks. Again, while the current system is a prototype, it highlights the potential of intuitive and adaptive human-automation partnerships, that allow for different autonomy levels to be applied based on context and the state of the human-operator.

Finally, human-drone interaction is an emerging area with a wide array of application areas ranging from automated delivery systems, to 3D displays, to photography and film, to gaming and entertainment. Drones have been used for carrying sensors, cameras, screens, and projectors as well as for providing tactile feedback and creating 3D displays [Funk 2018]. Automation and control levels of drones vary, providing a rich design space for applying TEI approaches for human-drones collaboration. Here we bring only one example of a human-drones interface, the GridDrones system [Braley et al. 2018b] (shown in Figure 8.20), but we encourage the readers to further explore this growing and exciting area. The GridDrones system, is an example of a human-automation interface where users interact with a swarm of co-located drones that behave as a single deformable 3D display. This system consists of BitDrones - cube shaped nanocopter drones, placed in a volumetric mid-air grid. Users create grid deformation by manually selecting a subset of the drones, then assigning a continuous topological relationship between the BitDrones and determining how voxels move in relation to each other. The

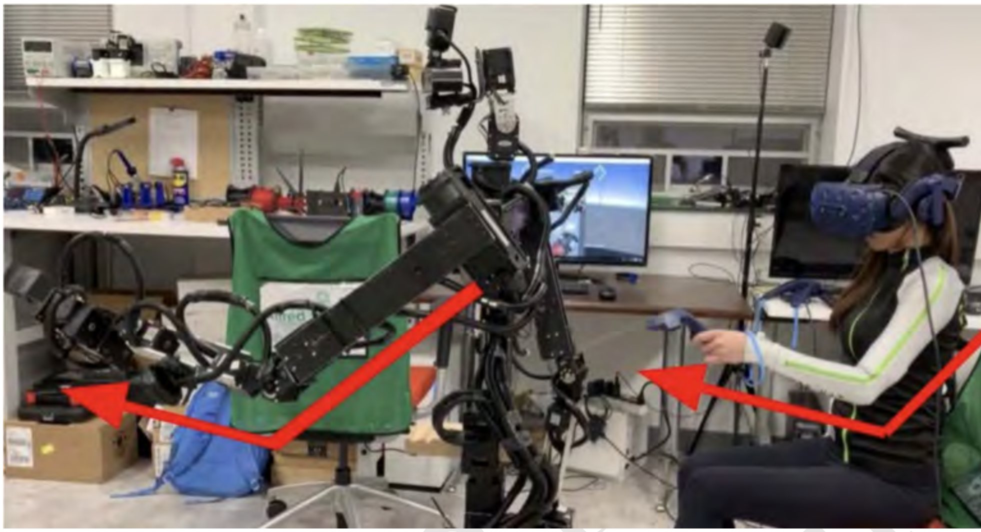


Figure 8.19 Telesuit is a wearable garment that allows the user to operate a humanoid telepresence robot [Cardenas et al. 2019a].

BitDrones are tangible and can be manipulated by hand through uni-manual touch, bimanual touch and gestural input. Unimanual touch is used to select single BitDrones, while bi-manual touch is used to select rectangular arrays and to rotate or translate the entire grid. Selection and other manipulations are performed using gestures. The topological relationship between sets of BitDrones through an smartphone app using touch interaction. The system also offers an embodied controller for children to easily interact with the movement and rotation of the grid (see Figure 8.20, right), as well as a simple tangible interface for the recording and playback of animations. The TUI is made active by pressing a menu button on the smartphone app.

These examples show the tremendous potential of TEI approaches to support new forms of human-automation partnerships. We expect TEI research and practice to help usher people into the age of automation, while promoting humanistic values.

Agenda for TEI Design and Deployment

- Form interdisciplinary teams to consider spatial, technical, social, and emotional aspects of human-automation interaction in order to accomplish a positive experience consistent with humanistic values.
- Design human-automation interfaces that make the state of the system visible, communicate how decisions are made, and allow users to predict and guide future moves.

Figure 8.20 Left (a-d): A user creates an archway from a 2x7 grid of GridDrones via ray casting with a "Point" gesture to select keystones. Once the keystones are selected, the user can manipulate them using a phone application. Right: A child interacts with the GridDrone butterfly animation using an embodied controller [Braley et al. 2018b].

- Design human-automation interfaces for people with different abilities, for different use scenarios, and support seamless transitions between different levels of automation and control.
- Design human-automation interfaces that facilitate awareness, self-reflection and deliberation on the power of users to disengage, alter, or customize automation for their own needs.

Associate Professor Andrew Kun, University of New Hampshire
Tangible Interfaces in Automated Vehicles: Interactions in Our Near Future

We are witnessing rapid progress in vehicle automation. Today's vehicles can assist the driver in a number of ways, including by recognizing speed limit signs and adapting the vehicle's speed accordingly, maintaining a desired speed without crashing into slower lead vehicles, and providing steering corrections to help maintain the vehicle within a lane. Yet, the driver is still in control of the driving task, and the automation only provides assistance.

Soon however, we can expect vehicles to take over the entire driving task, but only under limited conditions. For example, automation might be able to fully control a vehicle in slow bumper-to-bumper traffic on a divided highway. One exciting result of this progress of vehicle automation is that drivers will be able to engage in non-driving tasks during their trips. However, for the foreseeable future, they will only be able to do so for a limited amount of time, while the vehicle's context is favorable. Sooner or later, the automation will need to hand back control to the human driver. This means that the driver will have to stop the non-driving task they were engaged in during automated driving, and safely return to manual driving.

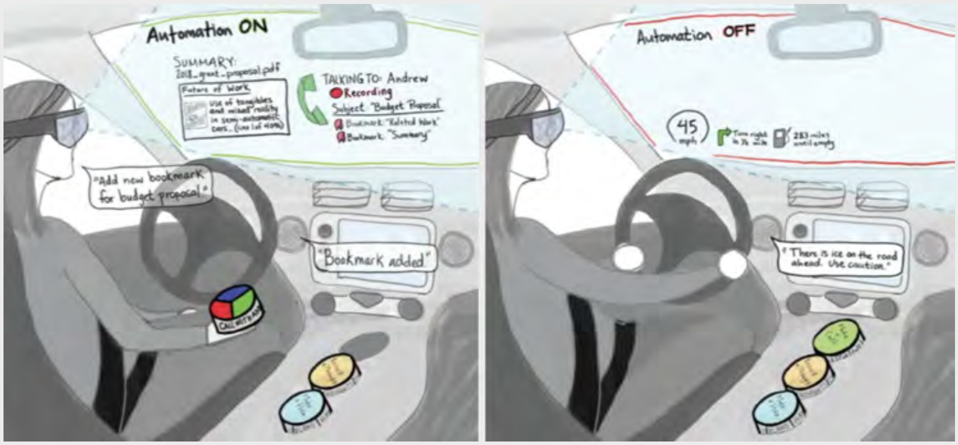
Thus, if we wish to take advantage of automated driving in order to allow drivers to work and play in the car, we will have to create user interfaces that meet two requirements. The first broad requirement is that the interfaces will have to make work and play possible in the vehicle cabin. The cabin is relatively small, and it is already full of interfaces that are necessary for manual driving. We cannot simply eliminate these interfaces to make room for new interfaces. Furthermore, if using the new interfaces requires looking away from the road, many users might experience motion sickness. The second broad requirement is that the interfaces will have to allow for a safe transition of control from the automation back to the driver.

Tangible and embodied interfaces are likely to satisfy these two broad requirements. First, they can co-exist with the established, mandatory interfaces of a vehicle, such as the steering wheel and gear shifter. Tangible interfaces can be small, and comfortable to manipulate without having to change the driver's position with respect to the vehicle's driving interfaces. Tangible interfaces can also be manipulated without the need to devote much visual attention to them, allowing the driver to keep their gaze on the outside world, and thus reducing the probability of motion sickness.

Second, tangible interfaces can support safe transitions from non-driving tasks to manual driving. The relatively small size of the tangibles will make it possible to quickly release them and place them in a safe spot in the vehicle. Furthermore, if the driver can keep their gaze on the outside world this will increase the likelihood that they have good situational awareness, which is necessary for safe driving.

Here is a look at how a tangible interface, in concert with augmented reality and speech interaction, could help us transform the vehicle cabin into a place of work during automated driving. The figure below shows a human operator in the car. She does not need to attend to the driving task while the vehicle is under the control of automation. Instead, she can focus on participating in a meeting using see-through augmented reality glasses. This device can display a summary of a document and information about an ongoing audio call. The driver's hands are free to manipulate the tangible interface. The interface allows her to take actions within the call (e.g., record, annotate, end call). There is also a speech-based interface to allow her to issue speech commands ("add new bookmark") and receive spoken feedback. The interface allows the driver to maintain her gaze toward the outside world. This helps minimize motion sickness as well as helps her retain awareness of her surroundings. The latter will help make it safe for her to take back control of driving, when needed.

When the vehicle requests that she take back control, the interfaces will support her. First, the interfaces will help her in wrapping up the work-related tasks, such that she is knows that she can later resume them. And, once she is driving, the interfaces will provide support for the driving task, or simply stay out of the way: the augmented reality glasses and the speech interface can provide navigation instructions, and the tangible interface can be stowed.



Vehicle automation will open up opportunities for work and play in the car. Tangible interfaces can help us take advantage of these opportunities. Images courtesy of Wellesley HCI Lab.

Andrew Kun is an Associate Professor at the Electrical and Computer Engineering Department of the University of New Hampshire. He received his PhD in Electrical Engineering, after which he spent two years in industry working as a development engineer for a oceanographic instrumentation manufacturer. Recently, his research revolves around exploring in-car user interfaces in driving simulators, and estimating the drivers' cognitive load to determine how the user interface influences driving performance. Outside of transportation-related research, Kun is involved in experimental modeling of collaborative user interactions around large-scale multi-touch displays.

Agenda for TEI Research

- What sensory cues are meaningful and effective for a positive human-automation dialogue, which promotes transparency and trust?
- What modalities are intuitive and appropriate for monitoring and controlling automation in different situations?
- Develop novel forms of human-automation interaction that allow for flexible task allocations and cognitive augmentation – facilitating attention management and reduced loads.

The socio-culturally embedded TEI community

The TEI conference was founded in 2007 and first took place in Baton Rouge, Louisiana. It recognized, and was fascinated by, the range of multi-disciplinary perspectives on tangible interaction. Hence, the conference brought together a broad range of disciplines including arts, design, architecture, engineering, computer science, psychology and philosophy. To value and stress the merits from these different disciplines, the TEI conference took an avant-garde approach and embraced a large variety of forms including talks, posters, panels, debates, demonstrations, art works, performances, student competitions and workshops, where all submissions were treated alike during reviewing and could be published on the same grounds based on their specific merits. The form of the conference aimed at expressing respect to all disciplines, openness towards showing and sharing 'crazy' new idea, and stressing the possibility for mutual learning, be it on practical toolkits, insightful user studies, stunning engineering, aesthetic, poetic or even shocking experiences, and deep philosophical questions. Fourteen years later, we still see participants from different disciplines and a wide variety of output forms, however the underlying spirit of crazy, open, avant-garde exploration of boundaries seems to have made place for more general multidisciplinary sharing and academic rigor. So, what is a TEI identity and what would we like our identity to be? Are we a community that wants to question Cartesian philosophical perspectives on life, and explore embodied alternatives? Are we aiming to move and be moved by beautiful and thought-provoking tangible and embodied pieces or art? Are we exploring grand engineering visions to make the world more tangible and embodied as an alternative for the overall present and dominating screen interfaces? Are we realizing societal and commercial impact through our designs? How do we make sure we are not re-inventing the wheel and see other people's methods and output as "toothbrushes", as it was coined by John Zimmerman - something we all have but never share? Do we want to be an incubator for new ideas and designs, off springs of the TEI vision, that jump into other fields and conferences as soon as they mature? Or do we want to be a separate TEI family embracing all ideas and designs related to tangible and embodied interaction? Or should we offer a platform for exchange between (young) researchers showing there fresh innovative ideas on the one hand and business and governmental parties aiming to implement some of these ideas.

The current societal protests and debate on racism and equality, make us also reflect on the TEI community, our composition, our attitude and our designs. Are we too uniform, excluding specific communities and voices? Are we focusing too much on Western world perspectives, communities and technologies? Are we putting high level technology too much at the center, ignoring many potential rich contributions about embodiment and situatedness with slightly lower tech solutions, thus having an unintended selection mechanism? Is our attitude open enough to embrace diversity? When looking at the entries of paper submissions at TEI conferences, we see a large variety of countries, but also continents that are not or hardly participating. What would need to change in order to receive more submissions from, e.g., South America or Africa? Is our community diverse enough in terms of culture, race, gender, sexuality, disabilities, etc.?

This year's TEI conference in Sydney, held just before the worldwide lock down due to COVID-19, seemed to have a predictive promising turn regarding equality and diversity, in various ways. There were several presentations showing culture-based technologies. There was a debate about the role of TEI regarding male-dominated healthcare technology, assessments and medicines, leaving the female body up till now fairly in the dark, for example regarding heart attacks, menstruation and menopause. And last but not least, the closing keynote speech was given by Angie Abdilla, CEO of Old Ways New, who tapped into indigenous knowledge from Australian Aboriginal people, thus drawing upon tens of thousands of years of culture and tacit knowledge, to develop new technologies, including tangible and embodied interaction. It shows the potential of the TEI community to address societal challenges from a diversity and equality perspective. It challenges us to explore and invite a diverse composition of people, have an attitude that is critical and reflective regarding our ethics and ways of working, and to develop designs which evoke respect and invite a large variety of people. This attitude and focus should in fact fits us like a glove. The very fundamentals of tangible and embodied interaction are supporting this view. Dourish [2001c] already emphasized the importance of embodiment and social situatedness, inviting people to create meaning in interaction, or as Jaegher and Paolo [2007] coined it: participatory sensemaking, where the whole is more than the sum of its parts. Technology per se is not the main goal of TEI, although that is sometimes the perception people have. We see the true value in the role of technology (lo and hi tech) as a mediator between people and the world, enabling them to create meaning in interaction.

PhD Candidate Dorothé Smit, Center for HCI University of Salzburg, Austria
Reintegrating Studios into Conferences

They say you never forget your first – and I don't know if that's true for everyone who attends TEI Conferences, but I remember my first visit well. It was the 10th anniversary of TEI in Eindhoven. The opening keynote that year was given by Takeo Igarashi, who showed his computer tools for complex 3D design on the most unassuming of PowerPoint slides. No pretense or embellishment, just some straight-forward live-demos of impressive software. This, I thought, is a community that I want to be part of.

I am now five consecutive visits to TEI in. Every year, I follow the discussions between the key figures and founding members of our community with great interest. In those discussions, there always seems to be a distinct melancholic longing for 'the good old days.' At the same time, there is increasing pressure to formalize our field, and to finally realize tangible user interfaces beyond the stage of prototypical instantiations.

I did not experience the good old days, but I have heard stories from many about the way the conference broke out of the established, graphical human-computer interaction paradigms and instead gave a podium to crazy TUIs and innovative embedded electronics. And I believe I have seen glimpses of that old TEI spirit in person – the Arts & Performance track at TEI 2019 Tempe comes to mind, or the demo session of TEI 2016 Eindhoven. The spirit is not lost.

This means we can work on getting it back. But what should *it* be? It seems that our community is torn between two ideals: formalization and solutionism, versus artistry, aesthetics, and engineering. But can't the two exist together? TEI is a conference in a unique position: a single-track conference, much smaller than, for example, CHI or UIST, but large enough that multiple trains of thought can exist. Yes, we should formalize our field, expand our theoretic foundation, and at least look at, if not share, our 'toothbrushes' – for the sake of the future of our community. But this does not mean there cannot be space for the avant-garde approach that many are missing now. In fact, we need to make space for the return of this approach, again: for the sake of the future of our community.

Sounds great, but how do we do this? I suggest we start small. I believe that the secret weapon of the TEI conference is one we often forget is unique: the Studios. No other conference offers this type of format, in which attendees can get hands on with the materials they are researching. It fits to TEI like a glove. Nevertheless, it seems that over the years, the Studios have gone from an integral part of the conference, to an afterthought. For comparison: in 2011, there were 13 Studios offered in the program. In 2020, there were three. The Studios seem to be considered a fun side-track, less important than the 'real' conference. I think this is a mistake.

In my opinion, the Studios are an excellent approach to bring back and evolve that old TEI spirit. But we need to get rid of the idea that Studios are somehow 'less than' paper or demo sessions, or that they should be embedded in theoretical workshops. Instead, the Studios should be viewed as an equal form of discourse: a conversation with the materials. The Studios are the prime opportunity to bring together engineers, artists, theorists, designers and philosophers in one room, and engage hands-on with the stuff that makes TEI tick: the tangible, the embedded, and the embodied.

Dorothé Smit is a PhD candidate at the Center for Human-Computer Interaction, University of Salzburg. Previously, she obtained her Masters and Bachelors degree at the Faculty of Industrial Design in Eindhoven, the Netherlands. She is currently writing her thesis, applying a Research-through-Design approach through a feminist phenomenological frame. In her thesis, she focuses on how digital/physical hybrid tools might support embodied sensemaking between people, especially in situations that might not be optimal for mutual understanding.

And that interaction is also important for the community itself. At the same memorable TEI 2020 conference in Sydney, Hiroshi Ishii called upon the community for striving to push the boundaries though envisioning the future, embodying original ideas and inspiring the people around the world with these visions, ideas and designs. To be able to do this, he stressed the importance of joining all disciplines. The question we have to ask ourselves in the future, is how do we want to collaborate, inspire and share our expertise and insights. A book is one way, a conference another, and there can be many more forms, for example multi-disciplinary student teams. Albrecht Schmidt, one of the founding fathers of TEI, called upon the community to remain avant-garde while having a strong drive towards an embodied world perspective, by questioning topics, developing innovations and doing the 'crazy' stuff that is difficult to publish elsewhere. According to him, the work that will become mainstream and bigger can easily be published in other venues and journals. One thing was very clear at the last TEI 2020 conference, a new generation of TEI-related researchers has entered the field, which might have its own ideas about the TEI community. It would be good to welcome a diverse new generation and offer them a platform, starting with a Vignette in this book.

Summary

In this chapter, which concludes the book, we shared our aspiration to bring in diverse perspectives for TEI to foster healthier, sustainable and more fulfilling lives for individuals and communities by leveraging and augmenting humans and their environment. This chapter is a call-to-action for TEI practice, research, design, and development to engage with enhancing creativity, productivity, collaboration, learning, imagination, inquiry, and social connectedness, while at the same time to consider ethical issues in design and apply responsibility. In particular, we highlighted three directions toward fulfilling such aspirations:

Deep engagement with societal challenges - developing and applying novel and established TEI systems, technologies, tools, methods, approaches and theories that anticipate and explore changing paradigms and that address grand societal challenges.

Fostering synergies across scientific, technology, engineering, art and design - forming partnerships to promote scientific discovery and technical innovation that augment human cognition and creativity, and support new forms of collaborations that bring together not only people but also other cognitive entities such as AI systems and robots.

And finally, envisioning socio-culturally embedded TEI community, which fosters multidisciplinary connections and takes an ethical stance to eliminate racism and address pressing societal challenges.

We expect that applying TEI approaches towards these aspirations will require developing the play field of TEI, pushing its boundaries by inventing new interaction techniques, novel design media, and different interactive technologies as well as the development of new paradigms and theories for the design, interpretation, and evaluation of TEI. We look forward to seeing the TEI community, and in particular a new generation of innovative leaders, rise together to address the grand challenges of our time.

9 Summary

In responding to a question about the potential pitfalls of TEI in a Zoom-interview for an undergraduate class at Georgia Tech, one of the authors of this book, Ali Mazalek, replied “we are currently living through one.” As we were wrapping up this first edition of the book, the world found itself in the middle of a pandemic – one that shut down cities, states and countries, and slowed the global economy at large.

To provide brief context on the nature and scope of the pandemic as known at time of press, on December 31, 2019, that the city of Wuhan, China, first reported cases of a pneumonia of unknown cause to the World Health Organization (WHO). On March 11, 2020, as the number of cases continued to rise around the world, the disease, then called coronavirus disease 2019 (COVID-19) and caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was declared a global pandemic by the WHO. COVID-19 is a highly contagious respiratory disease that is transmitted through close contact, primarily by droplets generated by talking, coughing, and sneezing, and by touching contaminated surfaces. While people recover from the milder form of the illness with flu-like symptoms, the more severe cases can cause respiratory failure, multiple organ failure, and other serious complications, ultimately too often resulting in death [He et al. 2020]. By June 20, 2020, there were more than 8.5 million confirmed cases worldwide, with more than 455,000 deaths [WHO 2020].

The COVID-19 pandemic raises many questions about the future of tangible and embodied interactions in a world where social distancing measures have been put in place across the globe, when it is unclear how soon we will return to our ordinary day-to-day lives, or what those lives may look like in the coming months and years. The vision of TEI is one in which computational media is embodied in physical objects, surfaces, and spaces that are touched and shared by many; one in which hands, bodies, and face-to-face collaboration are essential to the interactive experience. How does this reconcile with a world that has shifted largely to remote work; where person-to-person contact and the sharing of physical things is by necessity restricted? For the TEI research community, how will researchers conduct user studies? How will the broader community feel about encountering tangible systems in a post-pandemic world? Will people still feel comfortable touching shared objects and surfaces in public spaces, such as museums and galleries? These and related questions have been raised among the TEI conference steering committee and the broader TEI research community. Immersion within a global pandemic clearly has implications on the way we research and design tangible and embodied systems, on the way we teach tangible and embodied interaction courses, and ultimately on the way everyday people experience tangible and embodied media – and all our interactions with and through computation, our world, and each other.

One way we have engaged the current situation is in contemplating ways the TEI community can play a proactive role toward addressing the pandemic crisis. We briefly describe four projects we are currently undertaking in this respect. The first works to support underserved communities in producing protective equipment; the second, to enable remote work; the third, to facilitate learning, making, and collaborating for students at home or at a distance; the fourth, to envision new prospects for outdoor and hybrid fabrication/interaction spaces.

3D HELPS: 3D Health Emergency Learning and Preparedness Supports

Throughout the COVID-19 pandemic, personal protective equipment (PPE), such as masks and face shields, has been essential for the safety of both frontline community support workers and the general public. However, there have been shortages of PPE in many communities, particularly within the underserved. For example, within Indigenous communities in Canada, health care workers and residents rely on provincial and federal government support for PPE distribution during health crises like the COVID-19 pandemic. In underserved Indigenous communities, an outbreak could have devastating consequences – say, from fly-in-only isolation combined with a community's inability to rapidly provide care and protection [Brooke and Jackson 2020; Ferrante and Fearnside 2020]. To address the lack of both PPEs and guidance and documentation to support local PPE fabrication within communities, co-author Mazalek, and her colleagues Eric Liberda, Jason Nolan and Gabby Resch, all from Ryerson University, have partnered with the Aamjiwnaang Indigenous community near Sarnia, Ontario. This partnership will co-design and develop a toolkit consisting of materials, software and hardware tools, and techniques/processes to support Indigenous communities in creating the capacity to fabricate their own PPEs. By introducing contemporary "maker" practices [Browder et al. 2019] (e.g., rapid prototyping) to Indigenous communities, the project aims to increase pandemic preparedness and resilience, as well as access to STEM training and technologies in these communities.

Understanding and Enhancing Working from Home

The COVID-19 crisis has forced a large fraction of the adult population to work from home. As such, they are separated from their co-workers, lack access to tools found in their office, and in many cases experience frequent interruptions (for example, the need to attend to children). This situation presents an urgent need to support workers. To address this need, co-author Shaer and her colleagues Andrew Kun (University of New Hampshire), Linda Boyle (University of Washington), John Lee (University of Wisconsin), and Raffaella Sadun (Harvard) have refocused their NSF project on the future of work and wellbeing in automated vehicles (see Kun's vignette in Chapter 7), toward examining and addressing the needs of individuals forced to work from home. The project includes the development of a conversational agent for collecting data about workers' time use and wellbeing. The data will help inform the design of various virtual and augmented reality environments toward improving workers' wellbeing, productivity, and satisfaction. In particular, the team is developing virtual environments for reflection and relaxation, as well as augmented reality applications which enhance remote work meetings and foster more effective collaboration.

Learning Together at a Distance

Closely related to co-working at home, students are presently also forced to stay home. This can be challenging when, for example, a design student wishes to study and develop tangible and embodied interactions. To address and anticipate this challenge, co-author Hummels and her colleagues, Ph.D., Masters, and Bachelor students from the Transformative Practices (TP) squad (Industrial Design, Eindhoven University of Technology), together with the designer researchers and students from The Pink (RISE, Umeå, Sweden) refocused the TP and Comenius Learning Ecosystem research projects to facilitate blended learning. We developed dedicated platforms, tools and methods to stimulate joint learning and research at home, while embracing the principles of embodiment and situatedness. For example, we researched and/or developed embodied ways of reflecting, chatbots that stimulate casual encounters, robots to draw at a distance, letter envelope 3D printing models that can be easily sent by post for user testing, Carousel peer-workshops to engage student hands-on at a distance in each others projects, and many other experiments to explore the benefits of blended co-learning. Moreover, at the Department of Industrial Design, many other initiatives were sparked. As one example, the low fidelity/video prototyping website from Joep Frens supports students in experiencing the exploratory value of prototyping at home, while simultaneously teaching that prototyping and making are instruments for design. With careful part-time return to university buildings in the coming months, blended learning will realize an additional level of opportunities, where the 1.5 meter distance will give physical spaces new dimensions regarding the digital realm and learning together. Despite the horrors and drawbacks of COVID-19, blended learning ecosystems received an enormous boost; and TEI has much to offer in supporting their further development.

New Prospects for Outdoor Engagement, Hybrid Fabrication/Interaction Spaces, and Cyberphysical Editions

In much of the world, if there are not compelling reasons for activities to be conducted outdoors, they are partitioned within interior climate-controlled spaces. With COVID-19, this state of affairs is challenged, with interior interactions newly fraught for uncertain timelines. What if defaults could be flipped, with many activities (including computational ones) by default conducted outside? Such an exercise could prospectively also bring climate implications, given high energy and carbon footprints of HVAC; but remains deeply dependent upon particulars.

The opening pages of the appendix illustrate one such approach (albeit not limited to the time of COVID). Here, a CNC routed shelter modelled after Indigenous longhouses (in Europe, the Americas, and Asia, perhaps among other locales) is used to house interaction and fabrication resources toward "dual use" scenarios – supporting both research, education, and outreach in "good times," and a resource for quarantining, nightly habitation, and even perhaps intubation in difficult times. The envisionment also explores how directed solar illumination can be used as a display medium; how synchronized time-multiplexed actuation can reduce energy consumption while doubling as an audio display medium; and toward new paths for prospectively reduced environmental footprints.

In one additional variation, with all the envisionments of Appendix 1 realized in both physical and virtual forms, including virtual real-time illumination, students and others without physical fabrication resources can virtually prototype prospective TEI systems, and (with no intrinsic cost) scale these up, engage scarce materials, and envision synchronizations with remote cloud and human contents, in fashions holding value in or out of a pandemic.

Future Outlook

Beyond addressing the pressing needs created by the COVID-19 crisis, we propose engaging the situation by reflecting on the historical, philosophical, cognitive, and inherently human roots of TEI. While these remain open questions, both in ordinary times and certainly while in a pandemic, from the broader scope of history, this is not the first time that humanity has experienced a pandemic. The 1918 "Spanish Flu" pandemic, for example, infected some 500 million people, with a death toll at between 20 to 50 million people worldwide [Tumpey et al. 2005]. Although it may take months or years before a vaccine or herd immunity reinstates the level of comfort that we previously enjoyed, with close human proximity and shared physical experiences, we anticipate that return will come, newly complemented by all the new experiences we can collectively learn and create in the interim.

The pandemic helps us think about ways that we can more effectively address the health and safety implications of sharing physical objects, particularly in public spaces; but it does not imply any need to pivot away from TEI going forward. The reason for this, is simple: we are, and always will be, physical and social beings. In many respects, TEI's many demonstrated and latent potentials for mediating remote (human) presence, complementing the world's enormous acceleration in telepresence engagement, make TEI more relevant during and following the pandemic than ever before. We look forward to joining the TEI community in finding ways to engage and overcome the challenges of this present moment, developing technologies which capitalize on our fundamental human nature and on our physical and cognitive abilities.

APPENDICES

In evolving this book, we developed sections that are central to some of our TEI classroom use, but do not presently fit the core book's narrative arc. We migrate these here as appendices.

Enodia tangibles

In the authors' teaching of TEI across several decades, each have engaged a variety of commercial and custom technologies toward facilitating student projects. One of these, Enodia tangibles – designed in part specifically toward this book – is summarized here at more length. These are accompanied by open-source (for non-commercial use) resources for virtual and physical reproduction. Facets of these artifacts are discussed within the main book (e.g., §1.5 and Chapter 5). Figure A.1 provides several views of these tangibles, with features ranging from 1mm to 10m scale, and contexts from wearable to habitable.

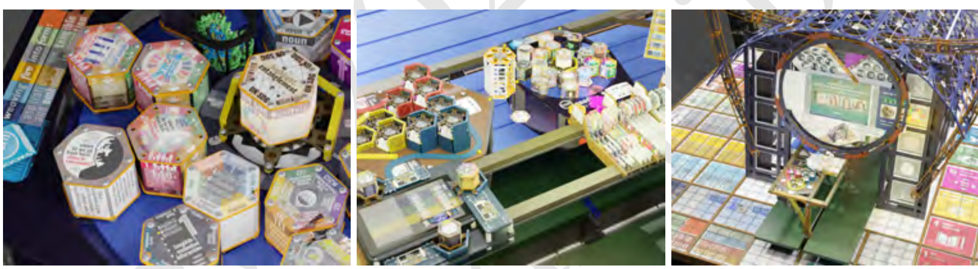


Figure A.1 **Several views of Enodia tangibles:** hextoks, hextok interaction devices, Ferntor Shelter

The tangibles illustrated in Figures A.1-18 began at the Dagstuhl Seminar on Ubiquitous Computing Education, held in June 2019. Stimulated by the hexagonal-tiled "Settlers of Catan" (of which more than 30 million copies have been sold in more than 40 languages); the COMB hexagonal tangible tiles of Rossmy and Wiethoff [Rossmy and Wiethoff 2018, 2019]; and a Dagstuhl set of hexagonal sticky-notes, Ullmer, Shaer, Konkel, Rinott, Mills, and Zeamer illustrated a set of hexagonal tiles expressing ubiquitous computing educational concepts (Figure A.2.a). When extruded into 3D space, such hexagonal tiles suggested enhanced manipulability (including toward collaboration) and supplementary visual real estate on their sides (Figure A.2.b). Figure A.2.c depicts a 3D printed physical prototype co-designed with Dr. Alexandre Siqueira, including integrated electronics for internal illumination. Shaer suggested use of such tokens to interactively represent and manipulate facets of this book.

With support from the US NSF "Enodia" MRI (major research instrumentation) funding, Ullmer and team began to operationalize this idea, including integrating it both within Clemson

Figure A.2 **Dagstuhl ubiquitous computing education tangibles**

University's TEI class, and within the grant's core goals toward supporting applied scientific research. Figure A.3 illustrates virtual and physical prototypes of these.

Two basic elements are depicted: hexagonal tokens (hextoks) and mediating "plinths" (an architectural term for foundation). As depicted, the hexagonal tokens are 5cm/2in flat-to-flat, and 3.8cm/1.5 in height. We have experimented with hextoks with NFC/RFID tags on their bottoms, or on one or two sides. In most of our designs, these are "skinned" with paper (whether opaque or translucent); but can integrate 3D models, epaper sides, etc. Per our subsequent illustrations, they are sometimes internally, side, and/or top illuminated; and sometimes proximally flanked with "digital shadows."

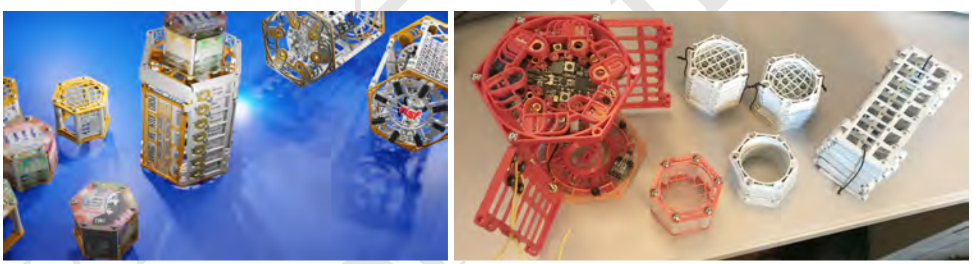


Figure A.3 **Hexagonal tokens (hextoks) and plinths**

The virtual prototypes of Figure A.3.a are modeled and rendered by the free Blender software, allowing rapid virtual exploration of candidate tangibles (including illumination). The physical tokens pictured in Figure A.3.b were fabricated with two 3D printing technologies. The red elements are printed in PLA on a commodity consumer-grade 3D printer. The token depicted was printed in 30 minutes (roughly 50-50 between upper and lower frames) with 2g of PLA on a CReality 10S Pro. The design depicted is rigid, with the top supporting printed materials, and both top and bottom largely transparent for illumination purposes. As depicted, these are linked with nylon spacers and steel 4-40 bolts + acorn nuts. This allows touch-selection of a face, either by touching the bolt head, or a coupled metal dowel pin. The identical design works with hardwood dowel pegs and glue, without the touch functionality and with longer assembly time. The white elements were printed on an HP JetFusion powder-based 3D printer, allowing ~300 hextoks per night to be printed (in full color) with unattended operation. Such hextoks could be fabricated in many ways – of solid or hollow wood, clay, cardboard, or steel; of glass, soil, found fill, etc. Our design choice related to economic reproducibility, minimization of plastic, and sustenance of a flat surface toward capacitive sensing.

The sides of the hex plinth are used to mount a Raspberry Pi Zero, optionally with epaper face; RFID/NFC readers; and sometimes, arrays of illuminated, metal-ringed touchpoints, allowing the vertical real estate to be used as an interactive surface.

Figure A.4 **Example hextoks skins:** a) top view; b) flattened, fitting A4 or letter page)

Figure A.4a illustrates a variety of prospective content represented with the hextoks. This overview shows only the tops of tokens. Much of the prospective real estate is found on their sides. Figure A.4b illustrates a both top + sides skin, along with several fixture points. These are arrayed for three skins to be printed on a single A4 or letter page. These skins can be cut with a CNC knife, laser cutter, or manually. We are exploring variations on this design for rapidly mounting and removing these skins, allowing a small number of generic hextoks to be remapped between a larger (prospectively print-on-demand) skins.

Multi-plinth hextok interaction devices

Figure A.3 illustrates the use of hextoks with a single mediated plinth. We have explored use of this both with audio content (e.g., per the internal speaker-support ring of Figure A.3.b); and association of the plinths with fixed room displays. That said, we presently find this approach holds broader prospective utility when multiple plinths are combined together. Figures A.5, A.6, and A.7 illustrate three complementary examples.

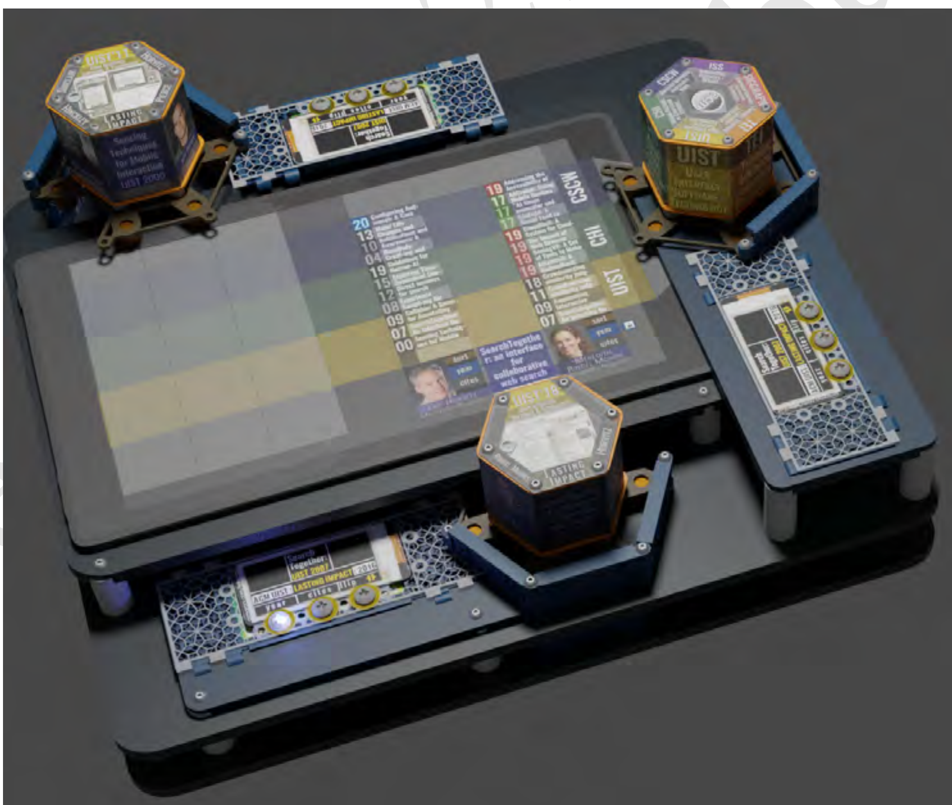


Figure A.5 **Hextok + epaper augmentation of a mass-market 10”-diagonal multitouch tablet**

In A.5, the mediating hexagonal plinth of Figure A.3 is reconfigured. The electronic paper and three illuminated touchpoint panel (composed of transparent polycarbonate bolts, capacitively-sensed bronze washers, and back-illuminating RGB LED strips) is reused, on its side, without modification. The three RFID/NFC 3D printed panels are truncated at half-height (the height of the commodity circuit boards). In this case, three readers allows a hextok tagged on two of its sides to both be identified, and have its orientation determined. Three such reconfigured plinths (again, identical in electronics and software to the plinths of hextok1 are used to surround three sides of a mass-market 10" multitouch tablet. Two different elevations of these bezels are adopted, to limit occlusion of the tablet by the hextoks.

The tablet is used to display digital shadows extruding from the six facets of the hextoks. Here, three hextoks are present: two representing UIST "Lasting Impact" papers, and one representing six interaction-focused ACM conferences. For the UIST tokens, hextok side-facets per-author are visible, as well as facets representing the title and summary of the award. In this envisioned application, the digital shadows intersect in a form of visualization spreadsheet, with each cell representing the intersection of the author activities in the selected venues. Sorting by year or citations is possible both via the multitouch screen and the illuminated epaper selection points.

In another variation, Figure A.6 depicts a prism of nine actuated hex plinths. These are identical to the hex plinths of A.3, aside from two variations:

- the incorporation of two additional side-facing epaper displays; and
- the incorporation of a traveling hex nut, to allow their vertical actuation along a threaded rod by an underlying stepper motor.

Figure A.6 **Actuated hexplinth prism** (above, side views)

This is an evolution of a student project (lead by Clemson students Sida Dai, Kwajo Boateng, and De'Quan Weldon) developing an actuated hex table and prospective applications engaging the UN SDGs. In the original student variation, a larger number of generic actuated pillars (inspired by the inFORM/transFORM system [] and the Giant's Causeway hexagonal basalt columns of Northern Ireland) were used. In the depicted variation, three triads of hex prisms are envisioned, with colored groupings and proximal epaper labels. A central hex plinth (visible to the right in Figure A.9 assigns the mapping of the remaining plinths.

In a third illustrative variation of ensemble hex plinths, Figure A.7 depicts a rotary hextok workspace. Here, a single motor, and two to six of the RFID/NFC side-faces depicted in Figure A.3, are used to identify and localize up to 18 hextoks. This actuating sensing approach is informed by the longstanding electromechanical design of hard disk drives. There, a central rotor spindle and a sensor on an actuated arm is used to access billions or trillions of data-bearing coordinates on the disk(s). In our variant, varying electromechanical geometries can scan 1D, 2D, or 3D rectangular or radial spaces of varying scales[1]. In addition, in the depicted variation, a single shaped RGB LED strip (visible in the rightmost cell of Figure A.7) can illuminate all of the hextoks, whether internally or externally. As with the hexplinth prism design of Figure A.6, an epaper display (including illuminated ? help buttons) is provided to offer contextual information.

Figure A.7 **Hextok rotary workspace**

In this particular envisionment, an actuated hex plinth (as within Figure A.6) is present within the center, hosting a hextok describing the computational mapping of the remaining hextoks (here, "highlight entanglement" with different forms of content). To allow this vertical actuation, the interaction device is depicted with a height roughly equal to the height of the

[1] In time, non-mechanical variations of such approaches may often be preferable. But at the time of press, actuated sensing approaches hold the potential to substantially reduce implementational costs,depending upon particulars – indeed, supporting functionalities and form-factors previously unavailable at any cost – among other attractions.

hex plinth + the height of an actuating stepper motor. That said, if sensing is realized by (e.g.) Microsoft Zanzibar or another non-actuated thin implementation, addressable LED ribbons of 5mm or narrower are presently available, and LEDs or OLEDs are available in minimal-thickness form, allowing the overall thickness to be almost arbitrarily reduced.

Where Figures A.5, A.6, and A.7 depict ensembles of hex plinths "in the void," Figure A.8 shows these and others suspended within a purpose-designed "railed table." This particular design uses three wooden rails to suspend and allow movement of interaction devices along a linear track. As the depicted interaction devices all have substantial depth, this approach allows the depth to protrude below the table. It also allows for relatively simple, lower-cost fabrication than a solid table design. (The voids depicted between unoccupied rails may in practice best be covered.)

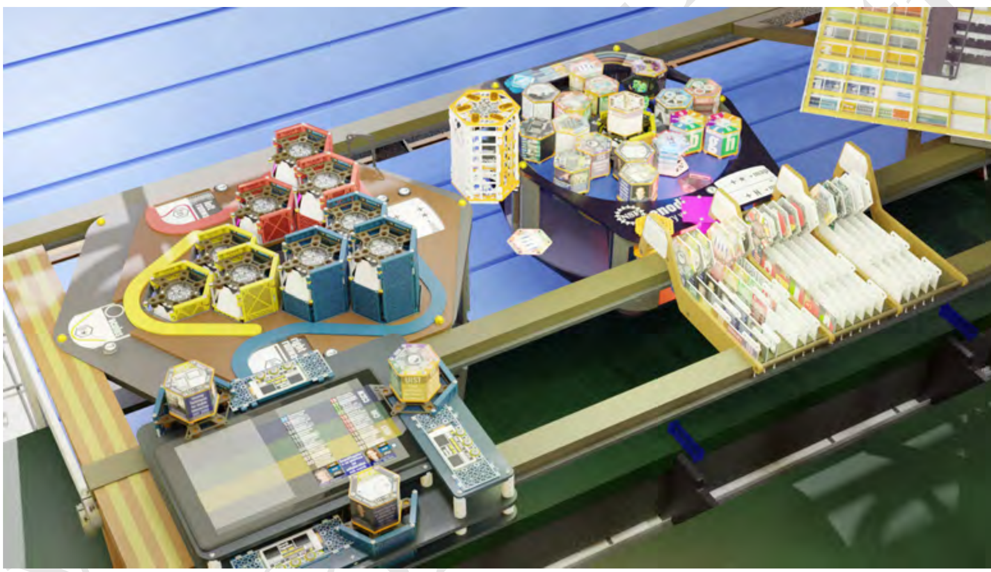


Figure A.8 **Hex plinth and hextok ensembles suspended in a railed table**

The fabrication of this table is illustrated in Figure A.8. Here, each table leg is constructed of three ½" layers of plywood, as cut by a 4'x8' CNC router. They are fixtured to each other by three 1" diameter pipes, with single-piece clamping shaft collars on either side. The off-center placement of the left pipe both increases rigidity by trigonalization, and provides a weight-bearing resting spot for some of the interaction devices (as pictured on the right of Figure A.8). Several ¼" carriage bolts and wood glue are used for increased rigidity. The rails themselves are sized either for (in the US) standard 1×2" furring strips and 2" wide wood strips, or CNC router fabrication from plywood sheets. (While sizing all components strictly for metric dimensions would give greater international portability, much greater variety and lower costs are possible by sizing to the standards of a given country. Other variations specific to metric sizes are to accompany on the website.)

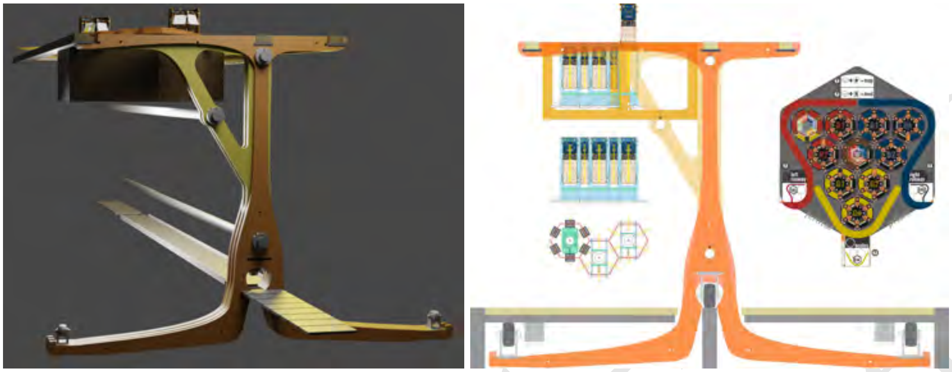


Figure A.9 **Ferntor table, 3D and 2D views**

As illustrated, the base fixturing of the table is unconventional. The middle of the leg is immediately above castors, which bear the table's weight as they ride along a floor- or ground-contacting wooden rail. The left and right splayed castors press up under a raised floor from beneath, providing stability. This allows the table to slide along the central rail. A fabric-backed array of lath wood travels to cover the floor slot, diving beneath the floor before and behind the table's present position. This design is motivated by the images and context of Figures A.10, A.15, A.11, and A.16.

Ferntor Shelter

In Jonathan Swift's 1726 "Gulliver's Travels," in relating experiences with the Sages of Lagado, Gulliver observes:

> since words are only names for things, it would be more convenient for all men to carry about them such things as were necessary to express a particular business they are to discourse on.... for short conversations, a man may carry implements in his pockets, and under his arms, enough to supply him; and *in his house, he cannot be at a loss. Therefore the room where company meet who practise this art, is full of all things, ready at hand, requisite to furnish matter for this kind of artificial converse [Swift 1727; Ullmer et al. 2016a].*

While a satire, we find many truths for tangible interfaces here. If literally regarded, the question is raised: what is the nature of such rooms, and how might they be more widely realized? Here, further import is suggested by anecdotal reflections on past technology deployments. For example, in Weiser's profoundly impactful "Ubiquitous Computing" article [Weiser 1991a], one of the three core embodiments were interactive (white)boards. This technology was productized with Tivoli and the Xerox Liveboard [Pedersen et al. 1995]. To our impression and awareness, Tivoli offered functionality in the early 1990s without 2020 equivalent – but at high cost. By reports of one of the leads, technology optimized for early-stage brainstorming was often sequestered in executive boardrooms – a poorly-fitting environ. To our understanding, this lead to one of the most common, fatal four-letter fates of bleeding-edge technology: dust (non-use).

In this context, where it is sometimes tempting to position ambitious tangibles deployments in the context of bleeding-edge technology-augmented workspaces, it is at least as interesting to consider their deployment in economically-reproducible spaces that are viable within a wide variety of buildings – and equally, outside buildings altogether. Partly in the context of the Covid-19 crisis, in contexts where outside spaces are available, this approach speaks to increasing capacity and decreasing density.

Figure A.10 **Ferntor Shelter:** Ferntor table, bench, Ferntor Oculus (with TEI course content), and mediated gates are visible.

Toward this, we illustrate several examples based upon the Shelter 2.0 design. First designed in 2009 toward engaging the homeless crisis, as a midpoint between tents and permanent structures, Shelter 2.0's ~open-source, CNC-machined plywood design for ~ $8{\times}8{\times}8'$ Quonset Hut/longhouse-like structures has since been widely replicated in locales ranging from Haitian refugee camps to MIT. As a platform for further augmentation, Shelter 2.0 brings established structural viability and a community of practice and deployment. This is so both in the physical form, and prospectively in virtual forms engaged through AR, VR, and other XR technologies.

Our TEI-specific variations on Shelter 2.0 are depicted in Figures A.10, A.15, A.11, and A.16, among others. We find it attractive from several vantages.

1. Many computational and manual TEI fabrication technologies (including CNC routing and mitre sawing) are noisy, dusty, and of potential danger. Both for inside and outside use, in augmented form, Shelter offers a platform for hosting and mitigating these.
2. A number of VR/XR tracking technologies require multiple high-positioned beacons. The trellises supporting these are commonly relatively expensive (e.g., > US $10k). Both in the core Shelter, and with the retractable wings illustrated in Figures A.11 and A.16, Shelter offers a fixturing platform.

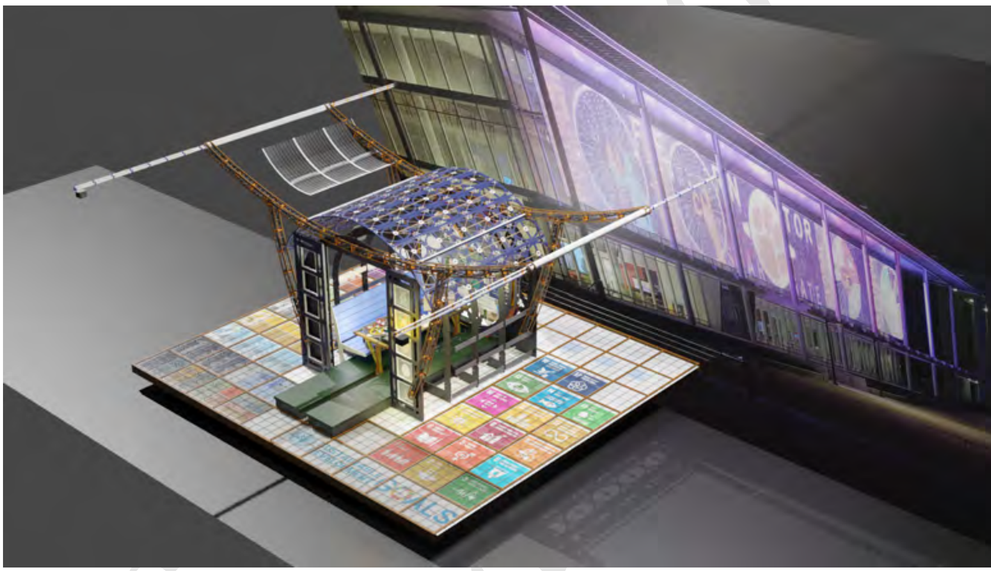


Figure A.11 **Ferntor Shelter, external view 1.** Here, the $8 \times 8'$ Shelter 2.0 variant is visible, with several external additions apparent. Among these, "wings" (retractable, in part for protection during severe weather) support sensor beacons on their periphery, flexible solar cells, and (in some cases) mosquito, UV, and/or IR netting/screens. (Infrared-opaque screens are relevant toward daylight operability of some mainstream infrared beacons, such as the HTC Vive.) A field/runway of labeled, actuated, potentially illuminated 2x2' cells surrounds the Ferntor Shelter. The Shelter's central table optionally slides out, as depicted and briefly elaborated in Figure A.15. An optically active roof is also visible, as depicted and briefly elaborated in Figure A.12. The Watt Center (at Clemson University), with an active low-density display facade (sometimes controlled by such structures), is visible in the background.

3. Many forms of display and mediation, ranging from one or multiple screens, to the actuated Oculus of our illustrations, require horizontal and vertical surfaces. Ferntor Shelter provides these in an economical, readily replicated fashion.

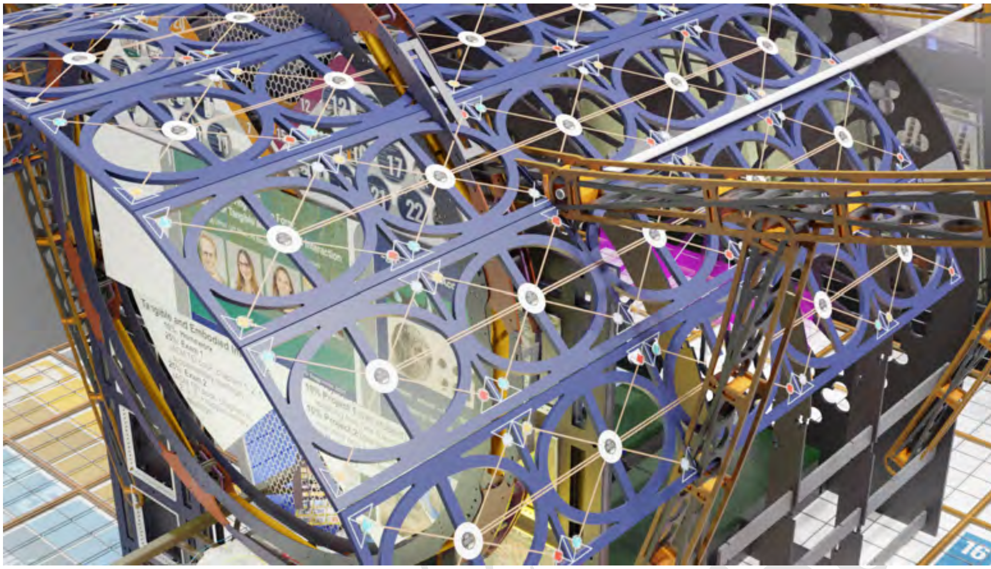


Figure A.12 **Optically active roof:** a trellis roof modeled after panels from the St. Chappelle's western wall stain glass windows is depicted. Individual "rows" are 8' × 16", allowing fabrication with many 16+" bed-width CNC routers. Each white-ringed point hosts a multi-channel analog/digital converter (here, a DFRobot Gravity I^2C ADS1115 16-bit ADC module). These are linked with translucent speaker wire to four splayed phototransisters, each faced by red, green, blue, and amber pieces of stained glass; and via a dual speaker-wire run, channel power and data to a per-panel Raspberry Pi. The A/D sub-panels act as low-cost 64 bit multispectral optical samplers. These are useful both toward orienting and optimizing the associated solar cells; and toward sampling ambient illumination toward a variety of ends (summarized below). The St. Chappelle-inspired lattice balances partial optical transparency with structural stability and light modulation (especially in sunny climates). The roof facets can be filled with polycarbonate or glass facets; or left open, with tarps pulled on-demand over the roof, or suspended from the wings. The roof also slides laterally, allowing improved external sun and rain shade and internal ventillation depending upon use case.

4. Both as discussed in Tangible Bits [Ishii et al. 2001a] and through the present, we remain deeply inspired by Raby and Dunne's envisioned remotely-synchronized benches [Dunne and Raby 1994]. Our envisionment bends the public benches of Munich, Germany both toward Raby+Dunne synchronization, with CNC router and 3D printers situated beneath.
5. Some of our envisioned applications may not be accompanied by wired-line power. Our envisionments illustrate (potentially orientationally adaptive) solar power (Figure A.12, likely toward recharging one or multiple integrate UPS power supplies.

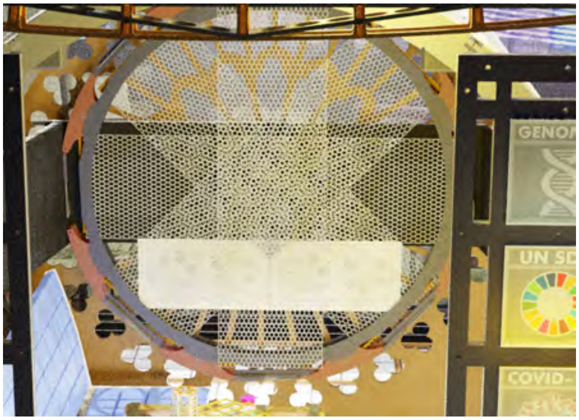


Figure A.13 **Example Ferntor integration from aspirational sources:** a) Rear wall of Ferntor Shelter with CNC routed-plywood framing deriving from Figure A.13b. Functionally, this framing enhances light and airflow passage, decreases weight and solar warming, and increases structural integrity and physical security. To enhance airflow in warm climates and/or during in-Shelter 3D printing, two commodity double-walled fans are depicted along lower third of the Oculus (to be reskinned more aesthetically), with four Oculus spokes rolled to hexagonal mesh segments for optical and airflow transparency.

6. In a variation on the "dual use" concept, where Shelter 2.0's origins sought to service homeless or otherwise transient people, those potentials are implicitly and explicitly retained in our illustrations. These include medical dimensions including quarantine and respiratory-support contexts, including (through the integrated fabrication equipment) the Shelter's ability to self-evolve its physical structure.
7. Outside deployments are subject to wind, rain, sun, insect, and other human engagement. Our envisionments work to modulate and protect against these.
8. The Ferntor Shelter is envisioned to be usable as a remotely synchronized structure. Partly inspirational to this, the Quanset Hut and Shelter are modelled after the best-known buildings of the Native American tribe most commonly known as the Iroquois. They refer to themselves as Haudenosaunee, or "people of the long house;" and to their confederacy of nations, the Ganonsyoni, as "the lodge extended lengthwise," with "all the individuals and all the tribes of the Confederacy... considered as one family living in one lodge" [Graymont 1975]. Our roof's multi-spectral photosensors (Figure A.12) is envisioned as coupled with ceiling-mounted RGB LED strips, to reproduce the light of remote spaces; the bench, as with Raby and Dunne's famous benches ([Dunne and

Raby 1994; Ishii and Ullmer 1997a]); and the Oculus, tangibles, and interaction devices, similarly ∼synchronizable.

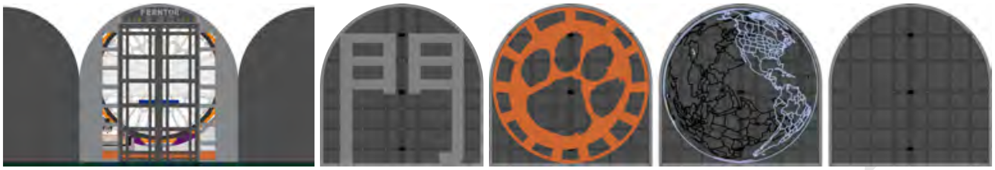


Figure A.14 **Ferntor Shelter outer doors:** for weatherproofing and physical security, outer doors (not depicted in the other renders) have been developed. a) Doors open. b) Doors closed; Japanese and Chinese character for "gateway" on face. c) Doors with a university logo (here, for Clemson University). d) Doors with a modified antipodal view of the globe, potentially to be augmented with capacitive sensing and LED illumination. e) Doors with only structural enforcement, to promote inconspicuity in deployment contexts where physical security is of concern. (e) might also be combined with variants such as (b), (c), or (d).

9. If asks "for what are buildings or rooms useful," many answers exist. Similarly, while we depict one configuration of the Ferntor Shelter, its prospective uses range as widely as that physically and/or virtually accomodable within its cyberphysical walls.
10. The Shelter 2.0 is relatively rapidly fabricated, assembled, and (re)deployable. We have maintained this character in our evolved design.
11. Synergestic with both our teaching, informal education and outreach, and broader goals, we have endeavored toward a low-cost reference design that could be regarded as aspirational in nature. Toward supporting and enhancing this aspect, our illustrated Ferntor Shelter includes evolved integrations of Notre Dame's north window (Figure A.13); St. Chappelle's western wall stained glass windows (Figure A.12); Ghiberti's Gates of Paradise; ceiling-motif from Whistler's Peacock Room (Figure A.3); Haudenosaunee/Iroquois longhouse; Munich public benches; popular circular envisionments of stargates; and the basalt columns of Giant's Causeway.

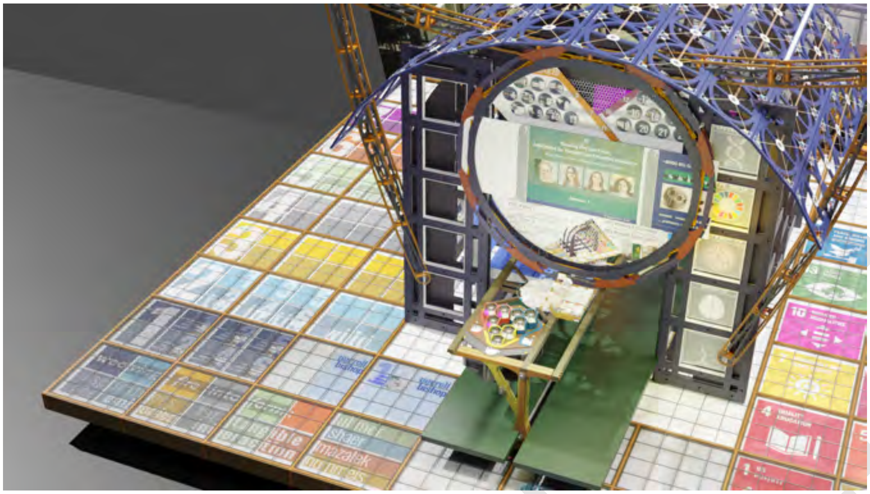


Figure A.15 **Ferntor Shelter, external view 2.** In Figure A.10 the circular Oculus was mounted inside the Ferntor Shelter. Here, it is mounted on the outside-front (with support for mounting on the outside-back). This configuration facilitates greater visibility outside the Shelter: e.g., with our planned outdoor lectures uses, partly toward Covid-19 response. The Oculus' round shape eases its movement (e.g., by rolling). The central table is depicted as slid along its track to an external configuration, allowing outside control of (e.g.) the Oculus and runway displays.

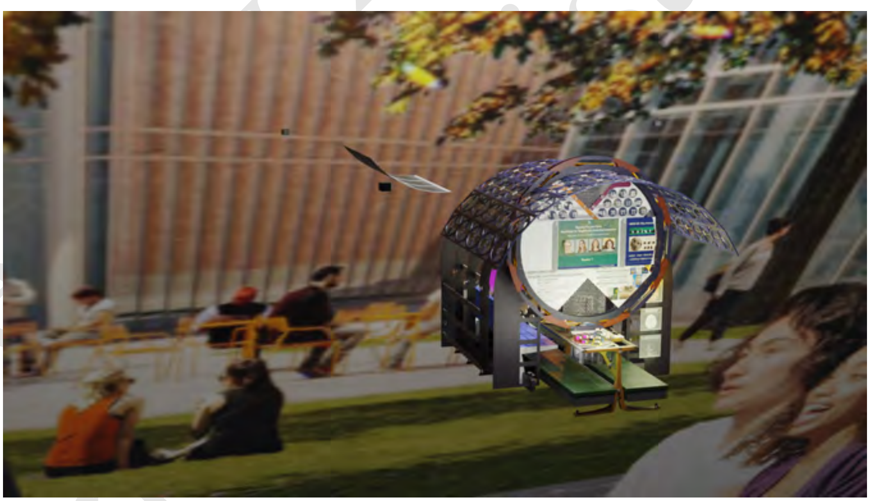


Figure A.16 **Ferntor Shelter: outside deployment without runway.** While the Shelter-flanking runway is illustrated in several of our envisionments, it is not required. E.g., this envisionment depicts an outside classroom prospect on a greenspace (perhaps driven by pandemic social distancing concerns), where potentially many relatively near-adjacent Shelters may be deployed. (Here, audio streamed via wifi to audience headphones may ameliorate sound contention concerns.)

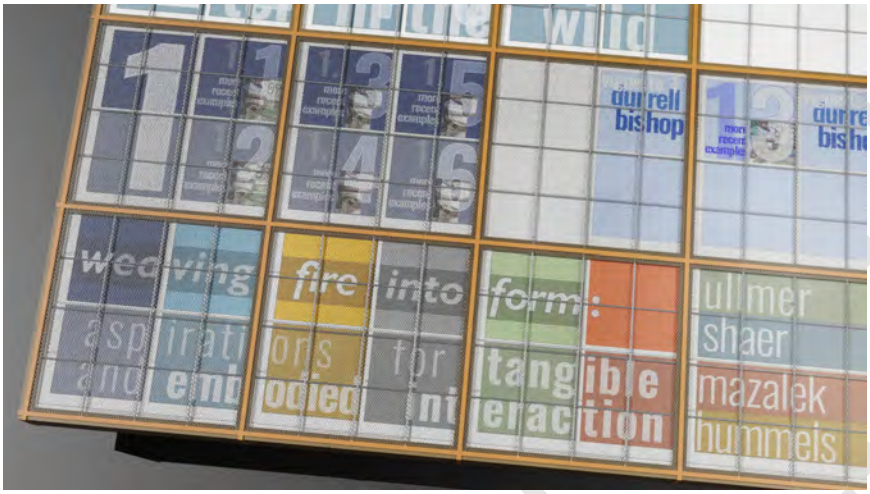


Figure A.17 **Runway inset.** In some variations, we surround the Ferntor Shelter with a "runway." Here, a metal hex perforated steel lattice atop an array of tensioned threaded rods, inset into CNC routed plywood frame, allows users to walk immediately above an array of printed materials. Figure A.10 depicts a left runway visually and textually summarizing the full contents of this book; and a right runway, the UN SDG. Here, an inset to the lower-left corner is depicted. These runways serve as an interactive visual display, controlled by the interaction devices and potentially complementary to materials upon the Oculus; an "invitation to interaction;" a contentful, semi-mediated walking path, including for AR and VR mediations, prospectively as well as the sight-impaired; and a backdrop for people and/or things tracked under the Shelter's wings, of scales or visibility requirements that cannot be accommodated in-Shelter.

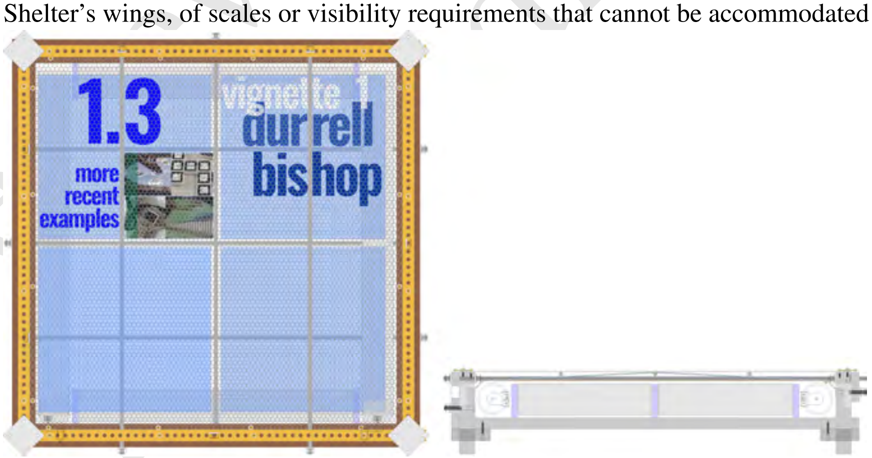


Figure A.18 **Runway substructure.** Top and side view of one of the 2'×2' cells. This illustrates 2' roll media on actuated rollers, allowing multiple floor contents to rapidly be selected. In low light, these are back-illuminable with low-density RGB LED strips. In bright light, a narrower, orthogonal, slightly vertically offset pair of rollers allows colored gel film to be slid atop the printed materials as visual highlighting. A tilted, heat-shaped polycarbonate shield deflects rain and soil. In further-elevated form, the runway can also serve "dual-use" purposes such

LAVA

This section previously appeared in an early version of the book as a half-chapter. The Enodia tangibles discussed in the previous section were developed in part as an illustration of the LAVA heuristics.

The LAVA heuristics – **L**egible, **A**ctionable, **V**eritable, and **A**spirational – provide another conceptual tool for regarding representation and control within interaction design in general, and tangible interfaces in particular [Ullmer et al. 2016a; Ullmer 2012b]. We elaborate upon these here, with special attention to different facets of *legibility*.

Legible

Are tangibles expressed in physical and visual representational forms that allow users to "read" them? In most rudimentary form, TEI legibility engages the question "what does a given tangible mean?" Legibility has many facets. For example, in contemplating Bishop's marbles, a given marble could potentially be associated with almost anything – be that digital (e.g., virtual content referenced via a web address), physical (e.g., a person, place, or thing), or conceptual (e.g., different ideas or challenges).

Textual legibility

One path toward legibility can employ text. This can be regarded from several altitudes – e.g., as a letter, word, sentence, page, book, or library. Relative to typography, legibility can be seen as regarding some threshold of size, contrast, obfuscation, and other properties in the context of a given human visual language. Several examples are considered in Figures A.19 and Figures A.20.

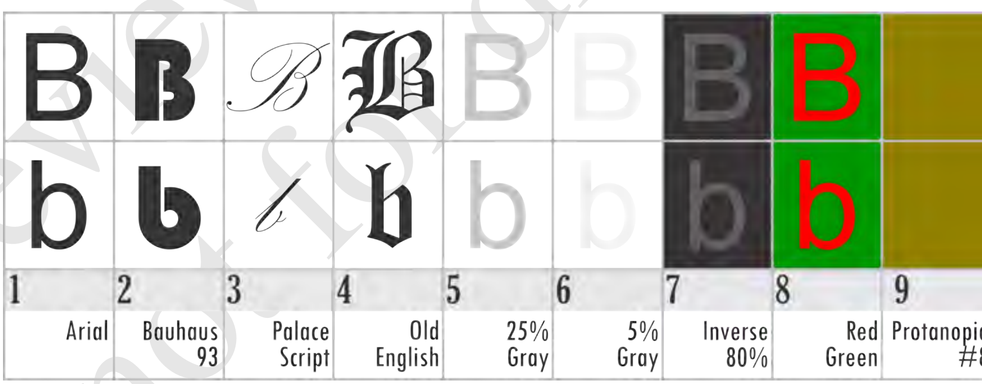


Figure A.19 **Textual legibility** (1/2): *Subfigure 9 generated by a simulation of protanopia, one of the most common forms of red-green color blindness, relative to subfigure 8.*

Specifically, Figure A.19 considers the letter "B" in a variety of typefaces and colors. The renderings of "B" within Figure A.19.1, in Arial, might be "legible" to most normallysighted people familiar with the Roman alphabet. With a rendition in the Bauhaus 93 font (Figure A.19.2), the more stylized forms might be legible for many people, but can also be seen pursuing (e.g.) a form study in curvature and constant-width stroke. In the Palace Script and Old English renderings (Figure A.19.3-4), the forms may be more consistent with "traditional" hand letterings than Arial and Bauhaus. Nonetheless, while Palace Script's "b" and Old English's "B" are highly expressive, they are also sufficiently divergent from modern norms as to challenge literal legibility for some readers.

Per our earlier discussion of contrast, Figures A.19.5-7 render Arial in three lower contrast variations. Depending on the display or paper rendering viewed, this reduction in contrast may be sufficient to obscure the letter altogether. In another variation, Figure A.19.8 is written with red-green colors, in a fashion marginally to completely illegible for readers with color-blindness. (Figure A.19.9 is generated through a simulation of protanopia, one of the most common forms of red-green color blindness.)

Along somewhat related lines, Figures A.20.10-11 depict two variations in the blurring of text (specifically, the "B" and "b" of Figures A.19.1). Here, the modest blur of Figure A.19.10 remains legible to most readers, while Figure A.19.11 is blurred to the extent of illegibility.

Why do these matter? As one example, 3D printing is presently a highly popular fabrication modality for the fabrication of tangibles. While full color 3D printing is sometimes accessible, single color is perhaps most common (especially if special filaments such as wood or conductive are desired). This speaks to the contrast variations of Figures A.19.5-6. Sometimes, high-resolution 3D printing is accessible; but lower resolution is presently more common (with substantial implications for print speed via the most common present-day processes). E.g., millimeter-scale print nozzles are presently common. This corresponds loosely to ~25 dpi – a very small fraction of inkjet or laser printer resolution. Without careful attention, or physical rendering of text via alternate means, 3D printed text can often approximate Figures A.20.10: functionally illegible.

In next variations, Figures A.20.12-13 illustrate approximations of "B" in alternate scripts. We see this as having several implications. If tangibles were labeled with letters, to support discrimination between otherwise comparable objects, there is no "universal textual language," equally accessible to all people. In a variation, textual and symbolic glyphs, while pervasively embraced by some communities – be they mathematicians, dancers (per Laban notation), or stenographers – may remain illegible to many.

Sometimes lesser legibility may be acceptable, desirable, or even existential. One example are the hobo notations of the 1880s to 1940s, marking which properties might be more or less hospitable. Here, and in many other past and future examples, "more legible" is not always "good."

Figure A.20.14 illustrate the letters B in collage context (here, by artist Itchi []). While the letters themselves are plainly legible, their meaning seems strongly colored by the evocative context – ambiguous to some, and perhaps quite clear (even denigratory or threatening; the

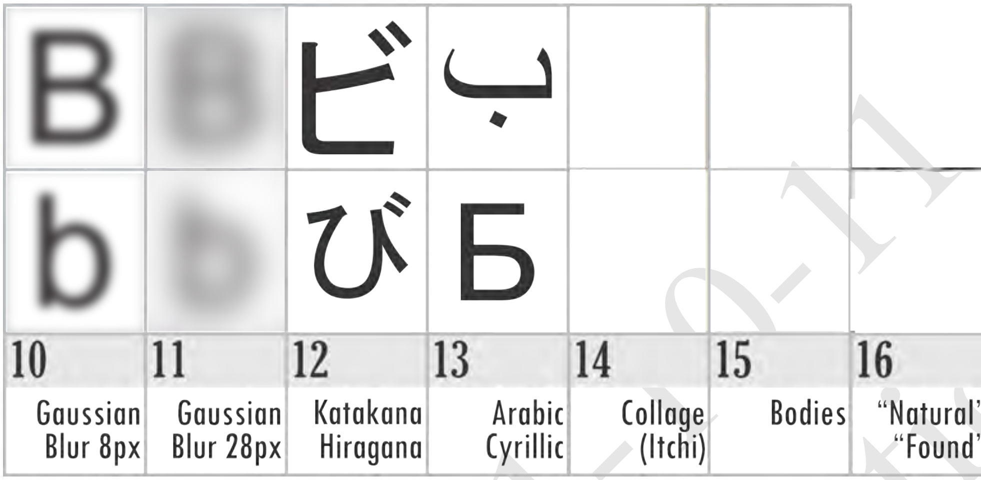


Figure A.20 **Textual legibility** (2/2)

authors remain unclear as to the artistic intent) to others. Somewhat similarly, the embodied evocation of letters within Figures A.20.15-16 – whether through the poses of children, dancers, natural materials, or "found" objects – each can substantially impact the literal and evocative legibility of the symbols.

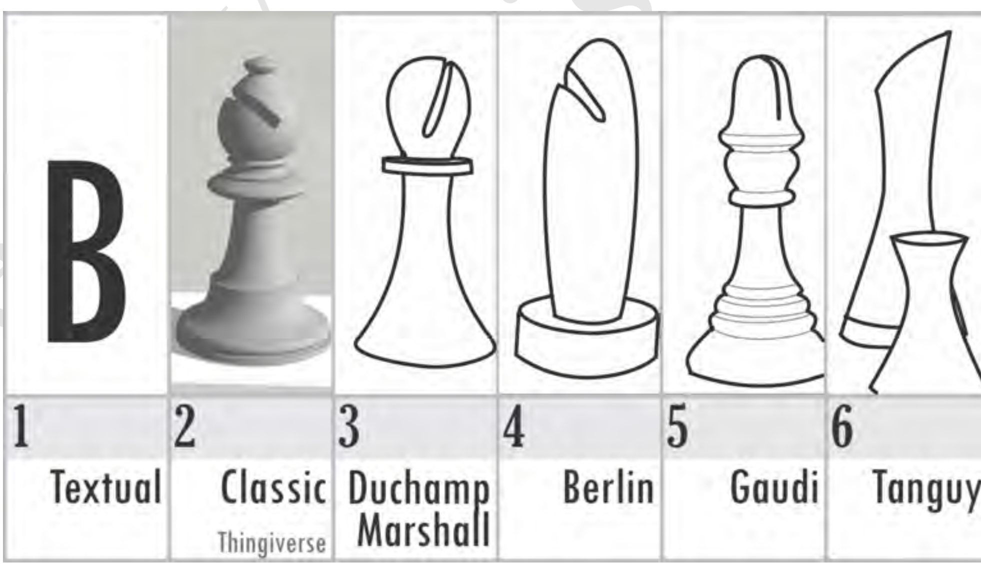


Figure A.21 **Legibility of form** (chess bishop, 1/2)

Form legibility

Next, we consider an aspirationally simple example within the language of physical forms. Figures A.21 and A.22 consider different representations of the chess game's Bishop. In written correspondence chess, Bishop is often represented with the letter "B" (as per Figures A.19-A.20). Figure A.19 represents a physical representation of Bishop in the standard Staunton pattern (here, per a 3D shape file present on the online Thingiverse repository, ready for 3D printout, VR use, or alternate employment).

Designer John Maeda has identified Marcel DuChamp (through his Readymades, where physical artifacts were asserted as an embodiment of a concept) as an early pioneer of tangibility. DuChamp himself was known for his decades of devotion to the Chess game, including championing the Marshall line of pieces. The DuChamp/Marshall Bishop (Figure A.21.3) abstracts and rounds out the more classic form. This abstraction is carried further by the "Berlin" variant (Figure A.21.4). In another variation, the "Gaudi" variation (Figure A.21.5) migrates the Bishop's notch (likely a stylized reference to the mitre hat, perhaps also to aid differentiation from the Queen and Pawn) to a symmetrical position.

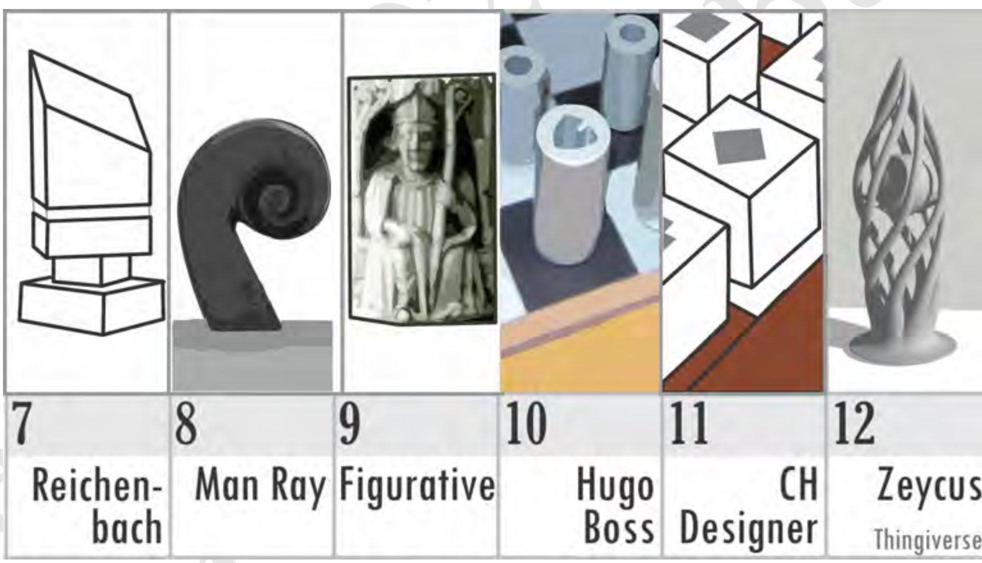


Figure A.22 **Legibility of form** (chess bishop, 2/2). *Reichenbach [Reichenbach 2014], Man Ray [man], figurative [fig], Hugo Boss [Museum], Chess House "Designer" [che], and Zeycus [Zeycus 2015] variations*

Beyond these thematic variations, many alternative styles have been developed. The Tanguy derivative of Figure A.21.6 further abstracts the diagonal notch to an obliquely truncated hyperboloid. For some viewers, this deviates sufficiently from "classic" Chess pieces as to be illegible – at least without the accompanying chess pieces for comparison. Figures A.22.6, 8, and 10-12 progress even further in this direction. Figures A.22.10-11 integrate 2D symbols – iconic of the mitre hat and the Bishop's dynamics of movement, respectively – alternately through extrusion and 2D labeling. (Figure A.22.7 also encodes the dynamics of movements in its plinth/foundation.) Alternately, in a ~12$^{\text{th}}$ century artifact, Figure A.22.9 expresses the Bishop in figurative form, as a pattern employed with countless variations.

One could argue Chess pieces to be among the most intensively iterated ecologies of shape language. Even so, perhaps half of the examples in Figures A.21 and A.22 might be unrecognizable (or here, illegible) to most casual observers. This speaks to the limitations of form alone for distinguishing the "meaning" of larger (e.g., web-scale) collections of tangibles.

Lynchian legibility

Our perspective of "legibility" draws heavily from Kevin Lynch's seminal urban planning text "Image of the City" [Lynch 1960]. There, he studied how several critical anatomical features of cities (Figure A.23) shaped both the physical structure of cities and people's mental maps of these spaces. He argued that how these compositional elements were employed (often over the course of centuries) had substantial impact on their legibility, as well as people's perceptions:

Figure A.23 **Image of the City:** *Lynch's illustrations of path, edge, district, node, and landmark patterns within urban spaces [Lynch 1960]*

> Just as this printed page, if it is legible, can be visually grasped as a related pattern of recognizable symbols, so a legible city would be one whose districts or landmarks or pathways are easily identifiable and are easily grouped into an over-all pattern.... Indeed, a distinctive and legible environment not only offers security but also heightens the potential depth and intensity of human experience. [Lynch 1960]

While cities and tangibles differ in scale and many particulars, we find this Lynchian sense of legibility of particular relevance and applicability. It remains unclear to us whether any correlaries have yet been realized for TEI. That said, several observations and possible directions are worth brief mention.

- Prospective analogues between Lynch's urban patterns and tangible applications would likely engage relations between physical and cognitive facets.
- Lynchian analogues might differ across different TEI structural patterns (spatial, constructive, relational, associative, gestural, proprioceptive, and performative). In this sense, where Lynch's patterns can be used to discuss most cities, the most evocative and pragmatically useful TEI analogues might be specific to particular TEI structural approaches.
- Holmquist et al's identification of tools, tokens, containers, and faucets (with less confidence in the latter term) has been attractive to many researchers. While their fusion of representational and functional facets can be limiting, it also somewhat parallels with (e.g.)

Lynch's landmarks (often marked by representational aspects) vs. edges (often marked by the shaped ∼absence of form).

- Ullmer et al. and Shaer et al.'s tokens and constraints/TAC [Shaer et al. 2004a; Ullmer et al., 2005a] model also holds partial resonances. Some early formulations suggested specificity to "relational" TEI patterns. But especially when both "hard" (physical) and "soft" (graphical or virtual) tokens and constraints are considered [de Siqueira et al. 2018; Ullmer et al. 2005a], TAC is applicable to spatial and (arguably) constructive structural approaches; and has spatial resonances with Lynch's urban patterns.
- While somewhat differently framed than Lynch's patterns, in resonance with McLuhan's "the medium is the message" the different technological and cognitive evocations of multiple forms of mediation – whether taken individually, or (perhaps especially) in combination – could hold Lynchian analogues. These include a range of complementary mediations (most of them surveyed in the previous chapter), briefly summarized in tabular form within Table A.1.

modality	passive	dynamic
visual	2D print	screen or projective
shape	3D form	actuated 3D form
configurational	2D/3D positions	actuated positions
material	traditional material	actuatable material *(electrorheological, electroluminescent, dynamic color, etc.)*
proprioceptive	static posture	dynamic posture
performative	static poses	dance

Table A.1 Complementary forms of mediation

- Of the several TEI analogues to Lynch's patterns, we anticipate that yet-unarticulated hybrids of one or multiple of the above – complemented by physical, virtual, or cognitive aspects we have not referenced here – could be more descriptive and generative than any taken alone.

Other legibility perspectives

Yet another perspective on legibility can be found in Lisa Heschong's "Architecture and Thermal Delight:[2]" [Heschong 1979]

> We need an object for our affections, something identifiable on which to focus attention. If there is something very individual and particular that we consider

[2] We thank Tom Erickson (IBM) for commending this example to us.

> responsible for our well-being – a stove that is the source of all warmth, for example – we can focus appreciation for our comfort on that one thing. [Similarly for "a lovely spring day," or a "tropical isle."] But... in a typical office building, to what can we attribute the all-pervasive comfort of 70°F, 50% relative humidity? The air diffuser hidden in the hung ceiling panels?

This example is particularly relevant to peripheral interaction's emphasis upon bridging graspable and ambient modalities of interaction [Bakker 2013a; Bakker et al. 2016; Ishii and Ullmer 1997a; Mankoff et al. 2003; Ullmer et al. 2016a].

For interaction design, how human engagement with such representational elements are mapped and transformed to specific computational mediations is a dominant concern. In the context of graphical interfaces, whether input is expressed via keyboard, mouse, touchpad, multitouch, the paths for initiating interactive are typically limited and constrained. For tangible and embodied interaction, the paths by which interactivity could be expressed are potentially much wider and more ambiguous. Bellotti et al. engage such issues with several of their "five questions for sensing systems" [Bellotti et al. 2002a]:

1. *When I address a system, how does it know I am addressing it?*
2. *When I ask a system to do something how do I know it is attending?*
4. *How do I know the system understands my command and is correctly executing my intended action?*

These alternate facets of engagement and mapping between people, artifacts, and computation also speak to the legibility of tangibles and interactions with TEI systems.

Actionable

Do tangibles provide paths to access and/or manipulate aspects of their cyberphysical associations? Most of the TEI systems we have discussed engage computationally-mediated interaction: touching something, moving something, throwing something – in short, *doing* something.

But – what to do; and, on first exposure to a system, how can one tell? Where our last section has contemplated "legibility" largely in terms of what a tangible "represents," a critical additional dimension is how the capacity for (inter)action is represented. Two common terms for this are "affordance" [Gaver 1991b; Hornecker 2012; Norman 1999] and "feedforward" [Djajadiningrat et al. 2002b], Djajadiningrat et al. have introduced and distinguished these so:

> Whilst there are many interpretations of affordance, most of these interpretations have in common that an affordance invites the user to a particular action.... With feedforward we mean communication of the purpose of an action. This is essentially a matter of creating meaning.... [Djajadiningrat et al. 2002b]

Two illustrative figures from these works are presented in Figure A.24. In the first, Gaver explores the relationships between provided perceptual information – e.g., visible or haptic engagement with a tangible – and underlying technological affordances (e.g., in the actions evoked by engaging a screen-based or tangible artifact). In the second, Djajadiningrat et al. reference the state of a system before, during, and following interaction.

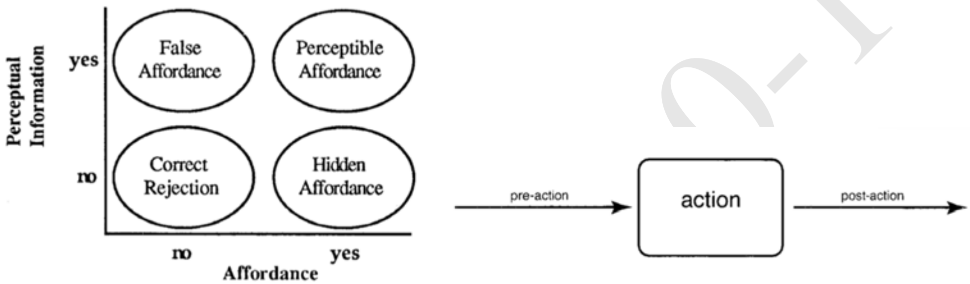


Figure A.24 **Affordance, feedforward conceptual illustrations:** From [Gaver 1991b] and [Djajadiningrat et al. 2002b]

In TEI contexts, prospective affordances can include the evident and actual ability of a tangible to be manipulated. Some of many examples include manipulation:

- in free space (e.g., lifted, thrown);
- on a supporting surface (e.g., shifted, rotated);
- relative to itself (e.g., squeezed, stroked);
- relative to other free tangibles (bunched, knocked);
- within or along a constraint (e.g., along a rod, in a groove); and
- toward a new constraint (e.g., placed in a dish, on a hook).

Per our cognitive discussions in Chapter 3 and within [Kirsh and Maglio 1994a], these actions can be epistemic (e.g., to aid cognition or memory, as with movement of Scrabble tiles upon a rack), or pragmatic – especially, to trigger some computational operation and mediation.

Gaver's illustration of Figure A.24a also illustrates the notion of a "false affordance." In a time of ubiquitous multitouch interaction, one common example is the presence of "illuminated glass" (a computationally-mediated graphical screen) as suggesting the capacity for touch/multitouch input. For people of every demographic (from youngest children to most senior computing academics), incorrectly assuming the capacity for touch input, when it is absent, remains very common – perhaps precisely for lack of a reliable perceptual affordance.

Toward TEI contexts, the integration of one or many buttons, dials, touchpads, or other integral interactors is common – albeit not always resulting in the most evocatively "tangible" systems. Another common approach toward supporting tangible perceptual affordances is placing a tangible relatively or directly proximal to a mediating graphical screen. Another regards the sculpting of a common design language suggesting actionable potential amidst an ecology of tangibles. Bishop's marble answering machine offers one example. More recent examples include using tangibles to control (e.g.) sound, light, or avatar upon some sister interactive artifact.

Materiality also offers another pathway for feedforward. Beyond "black glass" and plastic buttons, metal and conductive rubber lend themselves toward capacitive sensing. The artful integration of such materials into evocative objects, in combination with other tangible interaction artifacts and modalities, offers another pathway for evoking actionable potentials.

Finally, as noted by Wendy Mackay (INRIA) and in 2018 "Data Physicalization" Dagstuhl discussions, a multifaceted dynamic between "actionable" and "interactive" exists[3]. In particular, one can argue for actionable potentials within artifacts that are not actively computationally mediated. As explored in this book (including fleetingly within Table 1.x), in compelling online form within the Data Physicalization wiki [], and elsewhere, tangible and embodied representations of diverse associations and varying legibility have existed for many thousands of years. Most of these – then and (in the modern context of data physicalization) now – are not (presently) interactively mediated by computation. Parallels can be seen in modern diagrams. While a growing number of (e.g.) news outlets are heavily incorporating interactive figures, the majority of figures remain non-interactive.

One could declare such data physicalizations and sister artifacts to be "intangible," for want of interactive computational mediation. In our view, such a declaration would be both factually challenged and shortsighted. Factually, because a physical artifact that physically represent different associations (be they abstract data, or of people, places, or things) – by mainstream definitions, such artifacts would be regarded as tangible. One could easily argue whether data physicalizations are a superset, subset, or intersecting set relative to computationally-mediated TEI. In our present view, even for (e.g.) data physicalizations that are presently "non-interactive," there lies considerable potential for considering as tangibles, holding rich potential for future interactivity. In some cases, this evolution might be accelerated through anticipatory integration of NFC tags, conductive elements, unlit LEDs, etc., as footholds toward future awakenings.

Veritable

Do tangibles and their mediations provide means to ascertain the accuracy of represented content, and their interpretations thereof? With the Pinwheels of Dahley, Wisneski, and Ishii [Dahley et al. 1998b], the spinning of pinwheels was ascribed to (e.g.) changing stock market values. (This was later commercialized with the glowing glass Orbs of Ambient Displays [Felberbaum 2004].) Before the day trader acts on such stimuli, one might do well to ask: am I sure what I think is represented corresponds with "reality?" In a screen-based realm, with appropriate software, such indicators might be a hyperlink away from multiple corroborating

[3] The next two paragraphs were influenced by the 2018 Dagstuhl Seminar on Data Physicalization and by Wendy Mackay (INRIA). Our respect and thanks to all.

online news sources. Dahley et al.'s pinwheels, by contrast, had no screen, or alternate input or output pathway by which (e.g.) a Pavlovian classical conditioning causal association could be reinforced [Gormezano and Moore 1966].

In some low-stakes interaction contexts, there might be relatively little import if an errant or ambiguous ambient display is misunderstood. In others – e.g., defense response to an incorrect incoming missile alert [Nagourney et al. 2018] or indicator of proximal nuclear plant failure – the potential consequences are far more severe. Moreover, in a time of pervasive, consequential examples and references to "fake news" – substantially catalyzed and perpetrated by computational means – there is a special responsibility to pursue means by which TEI can support, rather than exacerbate, knowledge surrounding the veridity of mediations.

This is not limited to the machinations of a malicious "other," but rather a far more longstanding challenge with many TEI systems. In any TEI system involving a simulation – be it Underkoffler's 1998 Urp urban simulator tangibles [Underkoffler et al. 1999], Aish's 1984 energy profile simulator tangibles [Aish and Noakes 1984a], Phillip's 1948 MONIAC macroeconomic simulator tangibles [mon 1952], or hundreds of systems since – the underlying simulator makes models and assumptions that must not be confused with "truth." Efforts such as Mitchell Resnick (MIT)'s "Beyond Black Boxes" project [Resnick et al. 2000] have long sought paths to extend the "media literacy" project [Landay 1994] to the realms of simulation – and tangibles [Ullmer et al. 2017a].

Aspirational

Do tangibles provide aesthetic motivation to engage, and suggest paths toward creating like forms? Not all tangibles are equal in their potential to invite (or demand) engagement. Just as the potentials between an ill-conceived and executed art book, sculpture, or building differ profoundly from their aspirationally realized kin, the same is at least equally true for tangibles. This is not to equate "professionally-executed" or "expensive" as the inevitable target of tangibles. For a parent or grandparent, a young child's accomplishments with clay or popsicle sticks may well be an evocative, highly aspirational artifact – and, aspirationally for us, even a heavily mediated tangible. But it is to say that mileage and execution varies widely; and matter.

We would also note some a relationship between the terms "aspirational" and "inspirational." For several years, we used both terms, abbreviating them LAVIA. We experienced some challenge clearly differentiating the two, and uncertainty whether inclusion of both terms was more compelling for conceptual engagement than one alone. Wendy Mackay (INRIA) has noted that "inspirational" might be regarded as a "pushing" force, with "aspirational" as more a "pulling" force. While we have settled for some years on the LAVA variation [Ullmer et al. 2016a; Ullmer 2012b], it remains for the community to decide whether "inspirational," "aspirational," or a combination are most resonant.

Design guidelines

Human interface guidelines (HIGs) are "software development documents which offer application developers a set of recommendations. ... The central aim... is to create a consistent experience across the environment (generally an operating system or desktop environment), including the applications and other tools being used" [Wikipedia contributors 2019]. We consider several examples below.

- *Apple HIG:* Perhaps the most widely known and impactful HIG is the 1987 first edition of the "Apple Human Interface Guidelines: the Apple Desktop Interface" [Apple Computer 1987]. This was published some three years after the release of the Macintosh itself. On the order of a million Macintosh personal computers had been sold. From the Macintosh's 1984 release, the MacWrite and MacPaint software[4] had offered successful, widely-used exemplars of productivity graphical interface software. Also, by 1987, many independent Macintosh applications existed. In these important respects, the Apple HIG was not speculative, but rather articulating guidance on the basis of longstanding development and widespread use.

  The 1987 Apple HIG edition began with a chapter titled "Philosophy," including the sections:

  1. A view of the user
  2. General design principles
  3. Principles of graphic communication
  4. A strategy for programming
  5. Designing for disabled people

  Of these, sections 2 and 4 were the longest, with the following subsections:

General design principles	**A strategy for programming**
Metaphors from the real world	Modelessness
Direct manipulation	The event loop
See-and-point	Reversible actions
Consistency	The screen
WYSIWYG	Plain language
User control	User testing
Feedback and dialog	
Forgiveness	
Perceived stability	
Aesthetic integrity	

[4] Initially bundled with the Macintosh itself, MacWrite and MacPaint were unbundled in 1986, and spun off as Claris in 1987.

We provide these details for several reasons. The Apple HIG was an iconic, trailblazing document, with catalytic impact toward accelerating graphical interfaces to ubiquity. In some respects, a similar articulation for TEI would be desirable to many. However, we see important limitations and caveats to such an effort.

- *Non-WIMP, Post-WIMP, and Anti-Mac:* In one of these, some have noted that many of the most interesting modern interaction regimes by (e.g.) inverting many of the Apple HIG assertions. Some of these have been discussed under terms including non-WIMP[5] [Green and Jacob 1991], post-WIMP [van Dam 1997], and Anti-Mac [Gentner and Nielsen 1996]. For example, some have noted that "metaphors from the real world" can be limiting [Johnson et al. 1989] – even for "real-world" interfaces like TEI. Also, a relatively narrow, constrictive formulation of the desktop metaphor was originally expressed [Johnson et al. 1989]. We find these caveats worth recollection within TEI contexts.
- *Microsoft Pixelsense HIG:* There is opportunity and danger to be found in articulating design patterns and expectations before a given interaction ecology is well understood. For example, in 2009, Microsoft released its Microsoft Surface User Experience Guidelines [Microsoft 2008]. These included 24 interaction design guidelines. In some respects, these guidelines were visionary and potentially highly enabling. At the time of press, both the Android and Apple iOS app stores each contain roughly two million apps. In contemplations of comparable, or greater, futures for TEI, envisionment of the space and shape of present and future interactions could hold catalytic potential.

  In parallel, there is a danger that guidelines may constrict the space of the possible. As two examples, within interaction guideline 2.2.7 – "Provide a 360-Degree User Interface" – the guideline authors wrote:

  > ***Must:*** Orient the experience to its users by orienting new content or interface elements towards the same direction as the control (and thus the user) that created it. For example, if a new piece of content is a sub-experience|| of a larger one, and that larger one has had an orientation assigned to it by the user, respect that orientation.

  While there is an important underlying rationale, it is unclear whether TEI/Surface variations on spreadsheets – often regarded as the original "killer app" for personal computers – would be "allowable" under this constraint.

  As a second example, recollecting the first ACM CHI conference session explicitly referencing tangible interfaces (in CHI 2000), it is unclear whether any of the systems presented were consistent with (e.g.) the "emerging frameworks" discussed in [Ullmer

[5] WIMP refers to the windows, icon, menu, pointer paradigm of many graphical user interfaces.

and Ishii 2000a]. In our present view, this did not represent any inadequacy in the systems presented, but rather an overly constrictive conception of the TEI landscape.

Broader perspectives on implementation and mediation

Many other broadly-relevant technology heuristics hold relevance to the pursuit of TEI. We survey several of these here. Many of these draw from the business community. We see these as perhaps especially relevant (and in many cases, cautionary) to those with engineering and technology-development strengths and orientations.

Not Invented Here + Build vs. Buy:

Especially within TEI subcommunities oriented toward technology development and engineering, there is sometimes a tendency to blur the distinction between the *capacity* or *desirability* of creating a new technology, and the *necessity* or *strategic import* of this exercise. One variation has been termed *Not-Invented-Here syndrome*:

> the tendency of a project group of stable composition to believe it possesses a monopoly of knowledge of its field, which leads it to reject new ideas from outsiders to the likely detriment of its performance. [Katz and Allen 1982]

Sometimes this is an explicit rejection; often, it is implicit, from lack of awareness of alternatives. Sometimes it is born out of a desire to save money, space, or other resources. A related phrase is "build vs. buy" [Fowler 2004]. This resonates with a saying that the challenge of designing embedded systems is "not in the milliseconds, but in the months" [Poor 2001], in reference to the long design cycles of new technologies. The tradeoffs underlying this decision vary. For instance, within academic (and especially teaching) contexts, there is educational value in (re)creation, even if ready-at-hand alternatives exist. But with complex technologies often taking years to develop, this decision is important both to actively consider, and to revisit regularly as new technologies become available. This is of particular importance in that often the most time-consuming, least controllable facets of TEI technologies lies not only in the hardware[6] or software, but in the human communities underlying their use, development, and evolution.

Gartner hype cycle

The Gartner hype cycle presents a conceptual and visual perspective on the evolution of many technologies [Linden and Fenn 2003]. The cycle includes five phases in a technology's life cycle, the best-known being the *peak of inflated expectations* and the immediately subsequent *trough of disillusionment*. This cycle can be seen as having precedence for many sister technologies, including virtual and augmented reality, RFID, the Internet of Things, and 3D print-

[6] A related assertion attributed to Xerox Star co-designer Chuck Thacker is worth repeating: that computers (or other computational devices) without software are "no better than a hot rock – interesting but useless." [Smith 1999]

ing, among others. While popular attention is generally difficult to predict and short in attention span, TEI can be seen as benefiting from relatively long passage without particularly prominent mass media coverage, providing time for nurturing niche deployments amidst the longer trajectory toward broader, generalized adoptions.

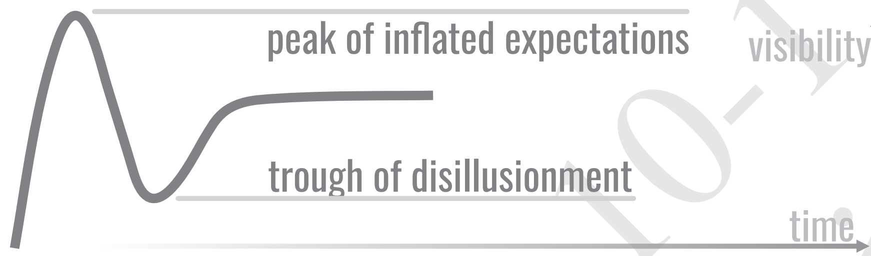


Figure A.25 **Gartner hype cycle**

S curves

S curves are another business-oriented perspective on technology evolution [Christensen 1992]. This tool highlights the dynamics of and relationships between successive waves of technology. Classical examples of this relate to the long gestation, explosive growth, and ultimate decay of audio and video recording technologies. For example, with video, successive S curves might represent VHS magnetic cassettes, followed by DVD disks, followed by online streaming services, to be displaced by other approaches. Related ideas include "creative destruction" [Spencer and Kirchhoff 2006] and "disruptive innovation" [Christensen 2013] Another phrase of broader relevance, and more diffuse provenance: "timing matters."

S curves can be applied within TEI at different levels of granularity. For example, at the embedded computing technology level, they could describe successive generations of embedded technologies such as the Motorola 6800, PIC chip, Arduino, Raspberry Pi, and their successors. At higher granularities, they could reference different technology toolkits – LEGO Dacta, and Mindstorms, Phidgets, Microsoft Gadgeteer, – or whole platforms, such as Compaq iPaq [Zigelbaum et al. 2007b], Sifteo cubes [Merrill et al. 2012], Apple iPhones, etc. Loosely quoted, the closing mantra in some MBA technology strategy classes is "life is busy; but each month, remember the S curves, at your company's peril." Even well outside of corporate R&D, this meme holds broad relevance to the TEI community.

Content vs. platform and Ansoff Matrices

In contemplating and pursuing realization of a TEI system, designers are often faced with the choice of building upon a pre-existing platform, or creating a new one. With substantial attraction in TEI surrounding materiality, form, and tangible ecologies, there is often a strong attraction to "begin anew" with new tangibles and a new system concept.

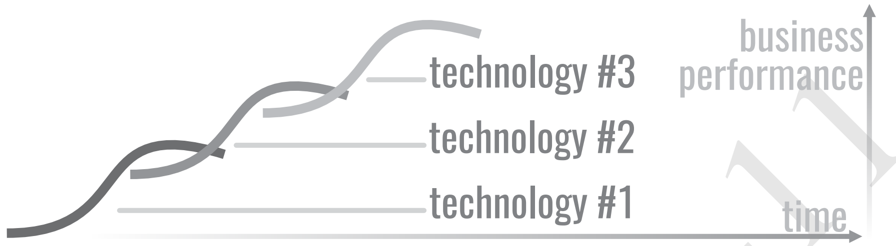


Figure A.26 **S curve**

	Existing Market	New Market
Existing Product Line	market penetration	market development
New Product Line	product development	diversification

Figure A.27 **Ansoff matrix**

Here, we see both opportunities and challenges; and commend both Ansoff (Figure A.27) and content/platform (Figure A.28) matrices for consideration[7]. First writing in the 1950s, Ansoff contemplated the relation between new and existing product lines, with new and existing markets [Ansoff 1957; Watts et al. 1998]. In a variant by David Liddle (manager of the Xerox Star) in his "Accounting for Electrical Engineers" course, the axes were existing vs. new products (or product lines, as a broader conception); and existing vs. new industries. There, a "danger of the two square move" – attempting to simultaneously create both a new product (line) and a new industry – was warned as often fraught with peril. In many business publications, this "new product+new industry" move is often referred to as the or "suicide cell." Even in deployments fuelled by massive corporate investment, many computing technology attempts to directly make a "two-square move" have failed (e.g., Xerox Star, Apple Lisa, Apple Newton, Microsoft PixelSense, and Sifteo Cubes, to name a few). Alternately, efforts to strategically, sequentially pivot in this space – e.g., with the Apple iPhone, as initially introduced without a capacity for external applications (per the "new industry" space) – have blossomed profoundly.

As technology evolves the face of the possible, a great many TEI systems simultaneously contemplate both "new products" and "new markets/industries." In parallel, there are dangers in conflating an embryonic demo with a viable product. Many deeply compelling TEI tech-

[7] The content/platform relationship was first observed to us by David Merrill, drawing from his experiences in leading the evolution and productization of Sifteo Cubes. Our credit and thanks to him for sharing this powerful concept.

nologies – e.g., Microsoft Surface/PixelSense and Sifteo Cubes, to name but two – had (in our opinion) deeply compelling platforms; but struggled, and eventually expired, due to a lack of "content." Similar assertions could be made over the last century regarding 3D movies, virtual reality, and many others.

	Existing Content	Community Content	New Content
Existing Platform			
New Platform			

Figure A.28 **Content vs. Platform**

Per David Merrill's formulation, Table A.28 contemplates this challenge in a relationship and symbiosis between platform and content. While uncertain of the exact formulation, we tentatively identify an intermediate phase of content to be "community content." For example, in the context of the Arduino platform (of which many millions have been sold), we would argue that early hardware releases were not accompanied by any key enabling "content" per se. Rather, they were accompanied by a compelling suite of development tools, amidst a community of makers; and this "community content" substituted compellingly for a more traditional set of well-defined "application content."

Again, in discussing the content/platform symbiotic interdependence, we do not mean to prescribe or exhort categoric avoidance of the "new platform + new content" space. Indeed, we regard the majority of TEI academic efforts to date as tackling this space. We see this both as a reflection of fertile creativity – but also, as a factor that likely has constrained or muted some aspects of mass market deployment in the early decades of TEI. We anticipate that progressive future blossomings of tangibility will – whether through serendipity or strategy – likely be enabled and shaped through navigation of this landscape.

C AUTHORS CITED

By academic tradition, references are often sorted by the last name of the first author. We provide such an alphabetized listing of references. That said, there are several limitations of this approach. In cases where (e.g.) substantial work is conducted in a faculty's laboratory, but students appears as first-authors, the collected work of the laboratory may be difficult to apprehend. Similarly, in cases where a given contributor always appears in a "middle position," the name may be difficult to identify. Toward these cases, here, we provide citations to all works referenced throughout this book, grouped by each contributing author. In the digital versions of this book, these citations are linked to full references.

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