Chapter 1
Introduction: A Short History of Tabletop Research, Technologies, and Products

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Abstract This chapter presents a brief history of scientific research into interactive tabletops, associated emerging technologies, and commercial products. It summarizes and visualizes a body of scientific work, identifies major advances during the past 15 years, and thereby draws a picture of the research landscape to date. Key innovations during this period are identified and their research impact is discussed. We synthesize historical information into a synoptic landscape including research highlights, enabling technologies, prototypes, and products. On top of this landscape, we point out and trace innovations as they stimulated and triggered key transitions in research and technology. These innovations have also played a major role in leveraging ideas from a conceptual level to widespread adoption and use. Finally, the chapter examines possible future trends of tabletop research, technologies, and applications.

Introduction

The rise of personal computers (PC) in the 1980s provided individuals with computational power on the desk in front of them rather than on a central mainframe. Interface designers structured and simplified user access to and interaction with data and information stored in these *desktop computers*. They turned the physical desktop into a metaphor for the Graphical User Interface (GUI) rendered on the vertical computer screen. In this manner the physical desktop itself shaped the way computers and information technology became integrated into everyday life. The idea that physical desktops play a central role when it comes to reviewing, organizing, and creating information that is not only paper-based, stems from the 1940s. This was when Vannevar Bush envisioned Memex, an electromechanical device for storing and reviewing information [1]. While technologies have changed dramatically since

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C. Müller-Tomfelde (ed.), *Tabletops – Horizontal Interactive Displays*,
Human-Computer Interaction Series, DOI 10.1007/978-1-84996-113-4_1,

then, his concept was later to be picked up and refined by Pierre Wellner when he presented the DigitalDesk in 1993 [2]. With this work, the computer display ultimately became a desktop, or as Wellner put it, "[no] desktop metaphor is needed because [the display] is literally a desktop" [2]. While the merger he suggested was consistent and compelling, research in the late 1990s showed that this interface would particularly add value to the work practice of small teams. This was also the period when various devices with new form factors such as laptops and Personal Digital Assistants (PDAs) became available. The advent of these devices in the early 1990s marks the onset of the era that Mark Weiser calls "ubiquitous computing" [3]. This trend has continued into recent times with the emergence of smart phones as well as netbooks.

The term *tabletop* stands in the tradition of earlier terms, such as *desktop* and *laptop*, highlighting the location of the computer or display. Tabletops distinguish themselves by being suitable as group interfaces and by the fact that their horizontal display is the interface where the user directly interacts with digital information rather than using the keyboard and mouse. In that sense, the tabletop is one of the interfaces where even the computer disappears, not only for the end-users [4, 5], but also for researchers exploring new forms of hand and gesture interaction, tangible interfaces, and novel interactive visualizations. This understanding of the term tabletop was first used in research literature around 2001 by Dietz and Leigh [6] and Tandler et al. [7].

Tabletop interfaces still maintain a notion of physicality as they rely on users' mental models of traditional tables. In contrast to virtual environments, where all sensory presentation is synthetic and most interaction is three-dimensional, tabletop interfaces are two-dimensional and better described as hybrid environments. Users combine the advantages of the physical environment with the possibilities of the digital information space. Rather than being dogmatic about which sort of reality or space users should work in, designing hybrid environments enables users to fluidly switch between and navigate physical and digital workspaces in an opportunistic way. Viewing a tabletop as a surface with electronic sheets of paper is an inadequate understanding of it as merely a horizontal display. Researchers and application designers will have to transcend this traditional user perception and take advantage of the possibilities that make interactive tabletops unique and fascinating. Inspired by Hollan and Stornetta [8], who question the efficacy of digital media replication of face-to-face communication, we see a need to "develop tools that go beyond" the work at traditional tabletops.

The first section of this chapter examines tabletop research in terms of Human Computer Interaction (HCI), Ubiquitous Computing (Ubicomp), and Computer Supported Cooperative Work (CSCW). The section goes on to present seminal research publications, enabling technologies, and commercial products. This is followed by a second section tracing key transitions driven by research and development since the late 1990s. Then, a third overview section graphically visualizes and contrasts selected landmarks of research, technologies, and products. The fourth and final section presents trends, again in terms of research, enabling technologies, and commercial products. The chapter ends with a discussion and summary.

Tabletops: From Prototypes to Products

This section first gives an overview of tabletop research in terms of key scientific publications. Then, it presents a set of important enabling technologies and how they benefited the design and realization of interactive tables. Finally, the section reviews commercial products from the last 15 years.

Research

Research into interactive tabletops and horizontal displays originated from and continues to be conducted within a few different research domains. Among the most important ones are Human Computer Interaction (HCI) and Computer Supported Cooperative Work (CSCW). HCI addresses individual user actions and performance at the tabletop interface level. The desktop metaphor of GUIs, as introduced in the early 1980s (e.g. Xerox Star), was a leading paradigm for simplifying interaction with computer resources. Interactive tabletops allowed for the opportunity to experiment with new forms and challenges of the user interface. In contrast, the CSCW domain addresses how computers can mediate and support group collaboration and social interactions. Each of these two domains provides an ideal community and forum to successfully "balance between good social processes and procedures with appropriately structured technology" [9].

In the early 1990s traditional HCI was inspired by Mark Weiser's paradigm of Ubiquitous Computing [3] (Ubicomp), which gained widespread prominence. Computer displays started to move beyond the form factors of traditional desktop environments, which had dominated until then. In Weiser's vision the yard-sized displays (36 inch or 91 cm) for collaboration were predominantly vertical, accompanied by foot-sized shared mobile displays (12 inch or 30 cm) and personal handheld displays (2 inch or 5 cm). However, by the end of the 1990s horizontal yard-sized displays also appeared as part of ubicomp scenarios for collaboration. In that sense Ubicomp inspired research into interactive tabletops. Finally, a key affordance [10] of horizontal displays is that their surface supports any physical object, making them an ideal setting for the seamless integration of tangible interaction on tabletops. Such integration is studied in the research domain of Tangible User Interfaces (TUIs). Hence, the four domains HCI, CSCW, Ubicomp, and TUIs constitute the scientific foundation and framework for tabletop research.

While the measures of task performance are well defined in the HCI domain for traditional desktop settings, measures such as object manipulation and movement times can also be used for interactive tabletop settings. However, tabletop task performance also involves more recent issues such as touch selection, physical reach, turn-taking, and verbal/non-verbal communication. In this sense, tabletop research is located in the CSCW category of *face-to-face interaction* [9]. Such collaborative work is diametrically opposed to, for instance, web-based approaches where spatially distributed users interact asynchronously. Another major characteristic of tabletop collaboration is that teams are typically small, seldom consisting of more than four people. Sugimoto's Caretta urban design system combining a tabletop with handheld PDAs [11] is a good demonstration of such small team collaboration. His system enabled its users to switch between private stylus-based sketching and shared tabletop planning. For larger groups, basic ergonomic issues emerge such as visibility and reachability of elements on the table.

As tabletop research is part of the larger HCI and CSCW communities, the most relevant publishers are the Association for Computing Machinery (ACM) and the Institute of Electrical and Electronics Engineers (IEEE). The ACM hosts the Special Interest Group on Computer–Human Interaction (SIGCHI) whose Conference on Human Factors in Computing Systems (ACM CHI) is a major annual international conference started in 1982. This conference is highly competitive and very relevant for the development of the tabletop research community. The ACM also hosts the CSCW conference, which was started in 1994 and is an important biannual conference addressing the collaborative aspects of interactive tabletops. Since 2006, the IEEE has hosted the International Workshop on Horizontal Interactive Human-Computer Systems (IEEE Tabletop). From 2009, the ACM supports this research activity by hosting the International Conference on Interactive Tabletops and Surfaces (ACM ITS). In 2007, the related ACM-hosted International Conference on Tangible, Embedded, and Embodied Interaction (ACM TEI) was launched.

To provide further insights into the body of research in the domain of interactive tabletop settings, we carried out a search on the Google Scholar web page accessed via the "Publish or Perish" program.[1] The search query terms were "tabletop," "interactive table," and "horizontal display," thus covering all publications including early ones that may not have used the term, "tabletop." For instance, Wellner's seminal work from 1993 [2] refers only to a "computer display [that] is projected on the desk" and does not use the term, "table," at all. The *top-ten* landmark publications listed in Table 1.1 cover a time period of over 10 years, and the number of citations ranges from 260 to 792.

While the citation figures may be read as indicators of relevance, they must also be considered with care since they come from only one database and do not reflect the length of time that has passed since publication. Also, these publications may have been cited for reasons other than tabletop research. The publications up to 1997 present experimental lab systems such as ClearBoard [18], DigialDesk [2], Bricks [12], and metaDESK [15]. From around 1998 onwards the key publications concentrate on systems for work environments with multiple users, such as the InteracTable in the i-LAND project [13], or introduce new technologies for the detection of multi-touch user input, as by the DiamondTouch in 2001 [6], SmartSkin [17], and then later by Han's 2005 work on FTIR [19]. It is a noteworthy that the publication about multi-user touch technology introduced by Dietz and Leigh in 2001 [6] is already at the third position only eight years after its publication (see Table 1.1). This is a clear indicator of the importance of multi-touch technologies for tabletop research.

[1] http://www.harzing.com/pop.htm

Table 1.1 Top-ten most-cited research publications on interactive tabletops. Citation numbers are based on a Google Scholar query carried out (4.8.2009)

Citations	Author(s)	Title	Year
792	Wellner	Interacting with paper on the DigitalDesk [2]	1993
532	Fitzmaurice et al.	Bricks: Laying the foundations for graspable user interfaces [12]	1995
517	Dietz and Leigth	DiamondTouch: A multi-user touch technology [6]	2001
479	Streitz et al.	i-LAND: An interactive landscape for creativity and innovation [13]	1999
422	Rekimoto and Saitoh	Augmented surfaces: A spatially continuous work space for hybrid computing environments [14]	1999
352	Ullmer and Ishii	The metaDESK: Models and prototypes for tangible user interfaces [15]	1997
329	Kato et al.	Virtual object manipulation on a table-top AR environment [16]	2000
314	Rekimoto	SmartSkin: An infrastructure for freehand manipulation on interactive surfaces [17]	2002
309	Ishii and Kobayashi	ClearBoard: A seamless medium for shared drawing and conversation with eye contact [18]	1992
260	Han	Low-cost multi-touch sensing through frustrated total internal reflection [19]	2005

To further understand the development of the interactive tabletop research domain we investigated the number of publications in the proceedings of the major ACM conferences, CHI, CSCW, and User Interface and Software Technology (UIST), from 1998 until 2008 as well as the tabletop workshops (IEEE Tabletop) held from 2006 until 2008. While the ACM TEI conference is not investigated here, we note that its 2010 call for submissions explicitly mentions interactive surfaces. A search with the logical disjunction of the three query terms “tabletop,” “interactive table,” and “horizontal display” was executed using an off-the-shelf file search tool[2] based on the Lucene[3] indexing and retrieval software. The results of this search query organized by conference and year are represented in Fig. 1.1. The figure shows number of publications, also referred to as hits. Each resulting publication is accounted for only once.

[2] Aduna AutoFocus 5, http://www.aduna-software.com

[3] http://lucene.apache.org/

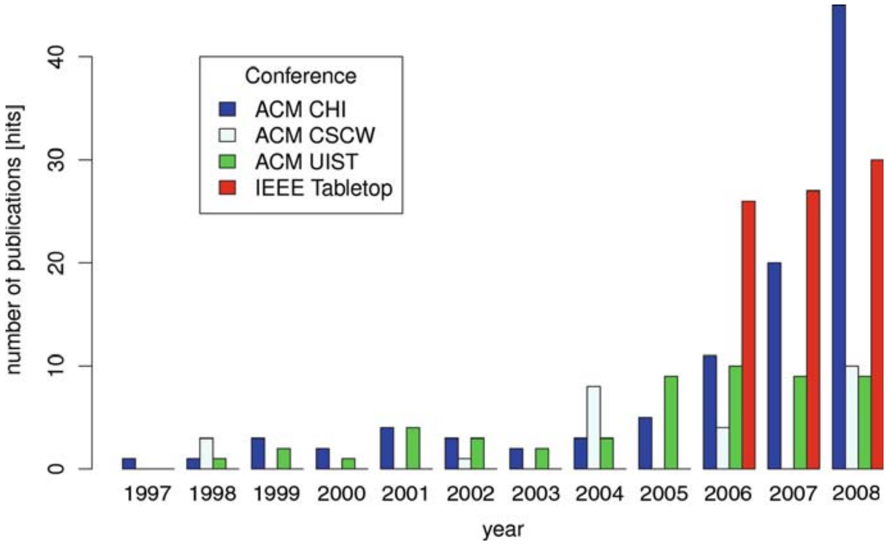

Fig. 1.1 Number of publications found in the ACM Digital Library. The query term was "tabletop" OR "interactive table" OR "horizontal display". Since 2005 the number of hits has increased for all major conferences, which is particularly visible for the proceedings of the ACM CHI conference

We assumed that all contributions to the proceedings of the workshop relate to tabletop research. Figure 1.1 reveals that from 2005 until 2008 the numbers of publications at ACM CHI has consistently increased. At the same time, the hits for ACM UIST increased from around three to nearly ten hits per conference. The IEEE Tabletop workshop, started in 2006 and turned into the ACM ITS in 2009, follows this trend as well. Another interesting observation is that the biannual ACM CSCW conference peaked in 2004 with seven publications, which is 15% of the proceedings. A detailed review of these hits revealed that these are highly relevant works in the area of interactive tabletops. The increase of publications in the proceedings of the ACM CHI conference could correlate simply with an increase of total accepted publications for the archives. However, a detailed analysis reveals that the hits represent 5% of all contributions in ACM CHI 2005, a percentage that increases yearly until 2008 when the hits were over 25%. However, it is not clear from the results whether a hit refers to a work of genuine tabletop research or the publication only refers to tabletops as part of related work. Extending the file repository with the proceedings of future conferences will better illuminate the historical trend in research and may give initial indications about future trends.

Enabling Technologies

Enabling technologies for tabletop systems can be identified in the areas of touch, display, and software, all of which are required to successfully build a tabletop system. Without a direct-touch device a system would be just a large screen; without a display the device would be no more than a graphic tablet; without appropriate software, interaction would be no more than what is offered by a simple pocket calculator. Early research systems used a large variety of general-purpose technology, such as video cameras and tethered tracking systems, to develop the prototypes. As time went by the technologies were further refined and some were adopted that were originally developed for other domains.

The origin of direct-touch devices can be traced back to 1971 when Samuel Hurst of the University of Kentucky invented the touch screen [20, 21]. He developed the first computer display that incorporated a transparent surface sensitive to touch. His guiding design principle was the precise detection of the location of a touch on a screen so that the display and input device could be used at the same time. Ivan Sutherland had demonstrated this earlier in 1963, however, in his prototype a pen or stylus was proposed to interact with the displayed information. Hurt's approach using the touch of the bare finger can be considered a very important step towards enabling touch screens and consequently tabletop systems. At the beginning of the 1990s large interactive wall displays were envisioned [3] and reliable touch detection became available. However, these touch technologies were rather basic and provided only a single point of interaction. From then on the refinement and development of exciting new touch detection technologies has had a significant role for tabletop settings. At the same time, stylus-based interaction on graphic tablets had been developed fulfilling similar requirements, only using a dedicated device. Various touch technologies have been developed based on resistive, capacitive, or acoustic sensors, optical triangulation using cameras or lasers, and computer vision using infrared image capturing. Key performance factors of touch technologies with relevance to interactive tabletop settings are:

- applicability to large display space (> 40 inch or 102 cm)
- reliable real-time multi-user touch capability
- low spatial requirements when integrating direct-touch devices into displays

Of particular interest in the near future may be the flexibility of the sensor technology with respect to the screen, that is, whether it needs to be planar or can be applied to, for example, curved surfaces [22, 23]. For widespread adoption in the market, low production costs are key. Data projectors, which became affordable in the late 1990s, allowed for a computer display that was similar to traditional slide shows and could be used on any flat surface. These projectors can be considered an important technology enabling the development of early, though bulky tabletop systems (see Fig. 1.2).

The development of large but sleek displays for the domestic entertainment market also stimulated research into HCI. Plasma Display Panels (PDP) with single touch overlay frames became commercially available around 1999 and were popular because of their large display size. This became the first alternative to large touch displays based on bulky rear projection, even when used in a horizontal tabletop setting [13].

Fig. 1.2 A typical example of tabletop system based on double-mirrored rear projection and a single touch interactive 1,024 by 768 pixel display. The InteracTable was developed as part of the i-LAND project in 1999 [13] and was further refined in collaboration with an industrial partner [24] with a Plasma Display Panel (Courtesy of Frauhofer-IPSI/GMD-IPSI)

PDPs have since then been outperformed by Liquid Crystal Display (LCD) technology [25], but they may experience a comeback if they can be developed into thinner form factors. Due to improved mass fabrication, LCDs have recently become available in sizes of up to 42 inch or 107 cm. These have been dominating the domain of large or yard-sized displays for small-group collaboration around a table. In combination with infrared video cameras for capturing hand movement and sensing touch interaction, these LCDs have the potential to become mainstream technology just as data projectors used to be. An important upcoming stimulus that may emerge from consumer electronics is the innovation of Organic Light Emitting Diodes (OLEDs). OLED technology enables slimmer displays combined with high contrast and better viewing angles [25]. The integration of the light emission into the pixel rather than using a backlight, as in LCDs, allows for thin display devices and new applications that were neither conceivable with PDPs nor LCDs. In general, display technology is a driving force in the development of tabletop systems, as new features such as depth and resolution allow for novel applications in combination with multi-touch and multi-user interaction technologies. A particularly innovative combination of hybrid display and light-based tracking was seen in Olwal's Lightsense [26]. In his work, a mobile phone was used as a "handheld lens" to examine layered map information on the tabletop.

Software and protocol standards also play an important role for the development of interactive tabletop systems. Standard user interfaces based on the paradigm of Windows, Icons, Mouse, and Pointer (WIMP) were not and are still not designed to support touch, multi-touch, and multi-user interaction. Still, this has been achieved, for instance, in pen input devices with special pen- or tablet-PC editions of operating systems. Furthermore, multi-touch pads have become standard for portable devices and are already supported by operating systems. However, while these extensions are rather moderate, supporting the characteristics of tabletop settings poses particular challenges for the software development. In some respects it requires solutions that are similar to groupware settings, as multiple users interact at the same time. Furthermore, while orienting the display horizontally the dedicated sides (left, right, top, and bottom) of the display change their significance. This has implications for how the software handles the display of information. Display areas may need to be rotated to an arbitrary angle to accommodate the perspectives of users around the table, just like it can be done with a sheet of paper. Early software solutions to offer such rotation were seen in BEACH [27] and DiamondSpin [28]. Today, similar solutions are achieved using hardware independent solutions such as OpenGL, Quartz, and DirectX. Other solutions, such as Simple DirectMedia Layer (SDL) and Windows Presentation Foundation (WPF), are more abstract at the price of reduced performance.

A variety of new approaches and solutions for tabletop software have been presented since 2000. Earlier research prototypes addressed the topics of collaborative work [27] and multi-user touch [28]. These highlighted the unique requirements of software for tabletop systems such as rotation and multi-user interaction and demonstrated possible solutions at the application level. At the input device level, the integration of single touch input into the software architecture of applications was as simple as with a computer mouse. With the introduction of multi-touch and multi-user input, event handling had to be redesigned to assure correct processing of the events at the application level. Also, aspects of multimodal interfaces became relevant for multi-touch input processing. Detecting a user's hand gestures requires applying the concept of fusion of multiple user input streams, for instance, for tracking two or more touch points of one or two hands, detecting object rotation or scaling gestures. These gestures became a standard component of the software of integrative table settings. Programming libraries such as touchlib and WPF have been developed to provide reliable access to the multi-touch detection technologies [29].

Furthermore, protocol standards, such as TUIO [30], emerged to propagate the touch interaction information through the level of layered software architecture [31]. An ultimate focal point of these efforts would be to make multi-touch input events an inherent part of the operation system. This would provide an environment that would be abstracted from the device layer, as is currently the case with the standard keyboard and mouse, to the application programmer. So far, research groups, direct-touch device hardware providers, and commercial application developers all use dedicated prototypes, tools, and drivers with limited applicability to the wider community of researchers and developers. Recently, systems were made commercially available allowing the development of tabletop applications where all required components come from one provider including hardware, operating system, and high level application software development kits (SDK) [32, 33]. While this may provide wider access to the development of tabletop applications, these systems are tailored for dedicated components and do not include generic software interfaces to the hardware and the operating system. These systems are designed for markets such as entertainment, sales, and education.

Commercial Products

Commercial products providing an interactive horizontal display have been developed over the past 10–15 years, but they have not yet reached the mass market. In fact, the early efforts in commercializing the concept of interactive tabletops were done by small enterprises in cooperation with research organizations or initiatives. These efforts cornered a niche market and garnered public attention. Only recently have larger companies with substantial research and development and public relations departments engaged themselves with interactive tabletops and developed products for the entertainment, education, and domestic domains. Interactive tabletop prototypes have also often served as an attraction at fairs and exhibitions.

One of the earliest products was the outcome of the Ontario Telepresence Project (OTP) [34], a Canadian research program for academic and industry studies into "sociological issues associated with the deployment of computer and video supported cooperative work systems." Among other results, the Active Desk and the Hydra picture phone system [35] were developed from 1992 onwards as part of this government research program. The "Active Desk [was] a large horizontal desktop surface" slightly tilted at a 30-degree angle and designed jointly by the OTP and a Toronto based company called Arnott Design Group [36]. It was also the device on which Fitzmaurice et al. did their seminal work on tangible Bricks, that is, Graspable User Interfaces [12]. Out of the Arnott Design Group's work grew another Toronto based company called Input Technology Inc. (ITI). Their patented VisionMaker product "[combined] the functionality of the graphics tablet and pen, with a computer monitor, making the two a single seamless entity" [37, 38]. The seminal work on the metaDESK by Ullmer and Ishii [15], in turn, built upon ITI's Visionmaker product.

In the mid-1990s the products of another Canadian-based company called SMART Technologies became increasingly important. The product line was called SMART Board, which was essentially interactive whiteboards. It took several years from their initial introduction until around 1997 before the large-sized interactive whiteboard became popular. They also introduced the first SMART Board for PDPs in 1999. Recently they presented a coffee table-sized multi-touch tabletop system for the educational domain: the SMART Table Model 230i [32]. However, eight years earlier the Germany-based office furniture company, Wilkhahn and later the spin-off *foresee*, started to distribute the second generation InteracTable [24], an office table based on the same technologies. This product was the outcome of a joint research and industry collaboration with the German research institute GMD-IPSI in 1999 [13, 39].

In 2001 researchers at the Mitsubishi Electric Research Laboratories (MERL) in Boston, Massachusetts developed the first multi-touch and multi-user tabletop device for collocated collaboration [6]. This research prototype was distributed to universities and fellow researchers in order to conduct research and develop applications. The device, DiamondTouch, was not commercially available until in 2009 when a company called Circle Twelve took over its commercial distribution [6, 40]. The years of active usage in the research community yielded a rich body of work from many researchers in various labs. Then, in 2005 researchers from Barcelona, Spain developed reacTable*, a tangible tabletop interface to control synthesizer software for live electronic music performances [41]. While this system may not be considered a typical consumer product, it has become popular within a niche market. It became famous as part of the 2007 live show of the Icelandic pop singer, Björk. Playing the reacTable* is compelling to the audience when observing the interactions of the musicians on the table while listening to the sound generated in real-time.

In 2005, Jeff Han presented a multi-touch technology [19] that was very inspiring and heavily broadcasted in 2006. He founded the New York City-based company, PerceptivePixel, to commercialize the Multi-Touch Collaboration Wall for use in broadcasting and medical visualization. From then on, various new companies emerged either by refining and integrating exciting devices and technologies or by building on a patented approach for multi-touch detection. The Helsinki-based spin off company, Helsinki Institute for Information Technology, began selling MultiTouch in 2008 making it the first commercially available multi-touch device integrated into a large LCD. Originally these “MultiTouch LCD Cells” were designed to form a multi-touch display wall, however, turned on its side a cell can act as a tabletop system [42]. A Swedish company, FlatFrog, recently introduced a multi-touch device based on a patented technology called Planar Scatter Detection [43]. It is unclear whether this technology has the potential to further improve the touch interaction experience, however, its close integration into LCD may allow the construction of a significantly less bulky device [42, 19]. Various other small start-up companies have been formed in Europe and the USA to serve a potential market for interactive tabletop systems.

To date, there are two companies distributing a comprehensive tabletop solution: Microsoft and SMART Technologies. While the latter company serves the educational market with its product, Microsoft targets the hospitality and entertainment industries. Both technologies are quite similar in their core specifications, but the design and style of the products are different. Both systems were launched around 2008, but the product development must have begun some years earlier. A key benefit for Microsoft might be that basic multi-touch capabilities can be realized in future releases of their operating systems: .NET and Windows 7. These systems are significant mostly because of the fact that end-users can purchase an all-inclusive solution that includes the hardware platform, software API, and, presumably, support. However, the core technology in these rear-projection systems with infrared, multi-touch capturing is challenged by cost-effective solutions adopted by Han in 2005 [19]. These technologies are currently being refined at universities and smaller start-up companies with the potential to construct new interactive tabletop systems.

Key Transitions

This section gives an overview of major developments and seminal publications marking significant shifts in tabletop research, technologies, and products. With the term *innovation* we refer to a seminal publication or an innovative technology that inspired and shaped the way research and development evolved from that point on. While innovations are usually marked by discrete events such as inventions and publications, we understand a *transition* as an abstract shift from the prevailing approach or paradigm to a new one. They may have either a more scientific or more technical character; as in most HCI-related fields, the cross-pollination of ideas constitutes a dynamic force for innovation. In the following, we identify and trace three such key transitions. They are not exclusive; we acknowledge that other less prominent transitions in this field may have occurred as well.

From Lab Prototypes to Real World Collaborative Applications

The emphasis of the early works investigating the use of horizontal displays and new approaches for computer interaction was on technical prototypes developed in labs. Projects such as DigitalDesk, Active Desk, metaDESK, Bricks, and ClearBoard realized technically challenging features and concentrated on novel applications. In retrospect, the importance of these works lies in the fact that research trends such as augmented reality, tangible interfaces, and distributed collaboration drove their development. At the end of the 1990s these research ideas were picked up and transformed into a new research context. Rather than sitting in labs as prototypical set-ups, novel approaches emerged, first for office and then domestic environments. Since that time it also became apparent that a tabletop setting is a piece of groupware. The BUILD-IT system from 1998 [44] and the InteracTable of the i-LAND project from 1999 [13] represent this transition in the direction of research. Both projects featured more than mere technical solutions; they also embodied new work practices using ICT. Work scenarios became envisioned that were grounded in real world collaborative activities such as planning and discussing. This included the identification of the tabletop setting as a highly suitable solution for small groups whether the team members are standing or sitting. More specifically, one aspect of the BUILD-IT project was the realization of real-time tabletop interaction with a connected simulation software system (SIMPLE++) [45]. Hence, collaborative production planning could be taken from individuals' PCs to the tabletop [46].

While application scenarios for interactive tabletop systems were originally identified for office environments, domestic and entertainment applications were later developed as well as systems for public spaces. As part of the Living Memory Project [47] in 2000, Philips Design created an interactive table situated and tailored for use in a café. In 2004 the Drift Table [48] was developed to investigate playful activity in the domestic environment. Interactive tabletop systems have also been deployed in various museums offering public new collaborative ways to explore exhibitions.

From Single Touch to Multi-touch and Tangibility

The first touch-based devices connected to computer systems essentially replaced mouse-based input and, as such, the processing of input events was done in the same manner. So while different physical input devices were developed, such as the touch screen and the pen or stylus, the input event processing in the operating system was not changed accordingly. Rather than tracking a particular point of input, TUIs empowered the interface by mediating objects that maintain natural tangibility. Reliable multi-touch capability was introduced with the Diamond Touch in 2001, targeting the requirement that the device "allows multiple, simultaneous users to interact in an intuitive fashion" [6]. The work addressed the drawback, at the time, of existing touch technologies that did not support concurrent touch interaction for co-located collaborative work at interactive tabletops. In 2004 this multi-touch device was complemented with a software toolkit for the "prototyping of and experimentation with multi-person, concurrent interfaces" at MERL [28].

However, single touch point interaction in a multi-user context still followed the pointing paradigm of manipulation in a graphical user interface. The pointing and touching gesture is only one possibility from the rich set of hand gestures than humans are capable of. Apart from earlier works [49], gestures in single user multi-touch tabletop interaction were recently popularized by the works of Wu and Balakrishnan [50] and Han [19]. Their demonstration of the abilities of multi-touch interaction broadened the interest in underlying technology and stimulated the research of gesture interaction on interactive tabletops complementary to the collaboration research domain. Along with this extension from multi-user to gesture-based interaction, TUI research received further stimulation. Although highly physical prototypes, such as metaDESK [2] and BUILD-IT [44, 51], had been developed in the late 1990s, tangibility became of interest again due to novel methods of tracking objects on the horizontal surface and the incorporation of ubicomp scenarios using mobile phones or other portable devices.

From Projection to Direct Display Technology

One of the crucial factors when considering the construction of a tabletop system is the display technology. Without a sufficiently large, hi-resolution, and bright display, tabletop systems may not fulfill basic requirements such as visibility and accessibility. The development of powerful data projectors in the 1990s stimulated research into user interaction with large displays beyond the traditional use of bulky and heavy CRT monitors. While early tabletop systems used front-projection, most systems thereafter applied rear-projection to avoid the occlusion of the display by the users' hands and forearms. Rear-projection also allowed for the particular illumination of objects placed on the screen. Outdoor usage is another challenge, as large displays are sometimes built into malls and street facades.

The consumer electronic market's focus on large affordable flat display systems for home entertainment was and still is a major contributor when it comes to suitable display technologies for tabletop systems. By the end of the 1990s, PDPs became commercially available with sizes of up to 52 inch (132 cm) and a chassis depth of around 4 inch (10 cm). The first interactive tabletop that used this novel display technology was the second generation InteracTable [52] equipped with a SMART Technology touch frame. At the same time, LCDs with a size of around 17 inch (43 cm) became an affordable replacement for CRT monitors. However, LCDs have only recently become available in sizes of up to 42 inch (107 cm) and with a 2-megapixel resolution. At this size and resolution, horizontal displays in tabletop systems significantly reduce the space required "behind the display" as compared to rear-projection systems. However, while these displays have the depth of a few inches, certain multi-touch technologies may still require as much space as rear-projection displays do in order to capture the interaction on the screen with an infrared camera such as in MultiTouch [42]. Recent research projects, such as TViews, Thinsight, and MightyTrace [53–55], highlighting the use of LCDs and novel technologies, e.g., as presented in [43], aim at the development of multi-touch interaction devices with reduced space behind the LCDs. For some niche applications on interactive tabletops, rear-projection, or even front-projection systems may still be the most suitable solution. However, in the foreseeable future effective multi-touch technologies may be integrated into flat displays without compromising the overall slim form factor of the system.

Synoptic Landscape

In this section we visualize landmark publications, enabling technologies, research prototypes, and industrial products in a synoptic landscape (Fig. 1.3). The visualization is inspired by the so-called *tire-track charts* as used in a US National Research Council report [56] to illustrate the impact of government-sponsored IT research and development on the economy. The clustering of the historical landmarks in the figure is primarily based on temporal proximity and secondarily on the categorization of research and products. We chose to visualize the three key transitions (yellow bars) rather than emphasizing technology transfer from research labs (red areas) to industry (blue areas). Contemporary research has not yet reached a high enough level of maturity, as based on citation ranking (Table 1.1), to constitute substantial

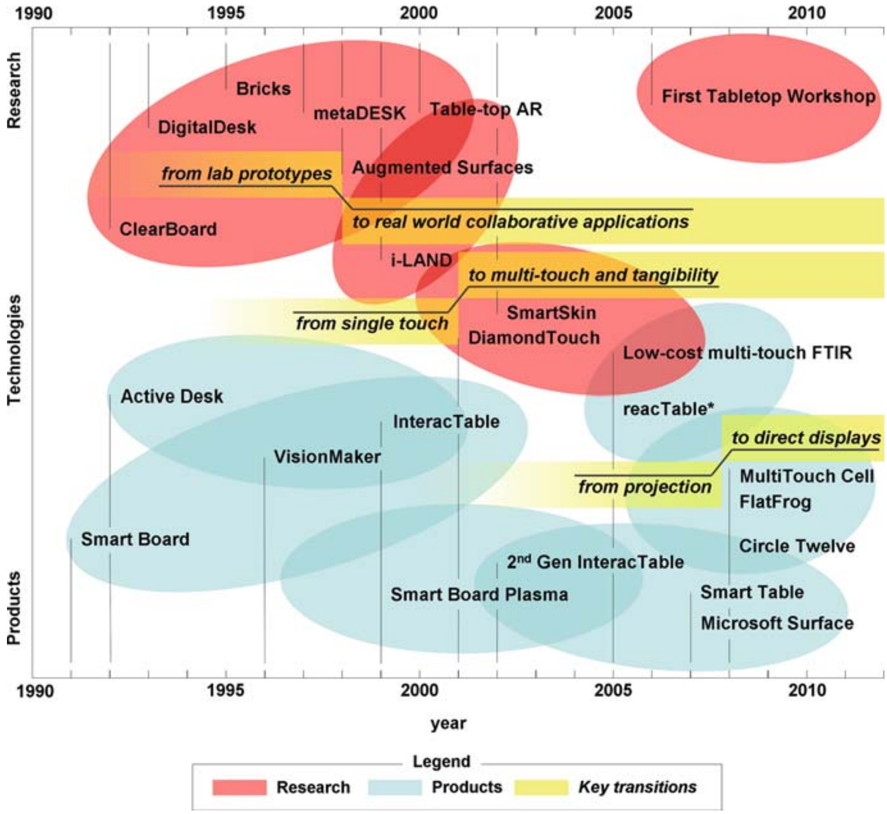

Fig. 1.3 Synoptic landscape of landmark publications, lab prototypes, and commercial products. For each of three key transitions traced and visualized we imposed a saddle point nearby landmark publications and products (1998, 2001, and 2008)

contribution to science. It is up to future investigation to find out what the research landmarks are after 2005.

Key transitions, marking when new concepts and ideas inspired and triggered new directions in research and development, are highlighted in Fig. 1.3. However, we are aware that early pioneering work always precedes the mainstream. For instance, TUIs had been introduced in the mid-1990s and were explored in early tabletop research work by Ullmer and Ishii [15] and Rauterberg et al. [44]; however, it was only in conjunction with multi-touch interaction technologies introduced in 2001 and 2005 [6, 19], that the tangibility aspect became popular in the tabletop research community.

In his article, "The Long Nose of Innovation," Bill Buxton argues that product innovation is "low-amplitude and takes place over a long period" [57]. In his claim to focus "on refining existing as much as on the creation" of new technologies, he recalls the history of the mouse pointing device. It was invented in the mid-1960s and developed into a ubiquitous and integral part of desktop computing by the mid-1990s. Indeed, the National Research Council (USA) states in their 2003 report on "Innovation in Information Technology" that there is a "long, unpredictable incubation period between initial exploration and commercial deployment" [56]. The council's report goes on to say that this incubation period needs "steady [research] work and funding." We apply their concept of a gestation or incubation period of up to 30 years to our synoptic landscape (Fig. 1.3) assuming that interactive tabletop systems will eventually hit the mass market. Marking the origin of the interactive tabletop landscape as Wellner's seminal work in the early 1990s, it may only be around 2020 that we will see the widespread use of tabletop systems. However, until then, early adopters in niche markets will be the first buyers of this technology and will stimulate the industrial development.

In retrospect, initial technology transfer from research lab to industry has already occurred but only on a modest scale. Government-funded research initiatives, such as the Ontario Telepresence Project [34, 36] of the early 1990s, enabled the landmark publication of Fitzmaurice et al. [12] in 1995, based on the Active Desk prototype, distributed in 1996 as a product by ITI, Canada. Another example is the collaboration between a German government research agency (GMD-IPSI, and later Fraunhofer-IPSI) and an industrial partner started in 1999, which led to the development of the second generation InteracTable [52, 24] distributed as a product by Wilkhahn/foresee, Germany in 2002. As a final example, in 2009, eight years after the landmark publications about the DiamondTouch [6], MERL decided to commercialize and distribute the technology via Circle Twelve, USA [40].

In the second phase of product development, larger companies such as SMART Technologies and Microsoft developed multi-touch tabletop systems that have been commercially available since 2008 (Fig. 1.3, lower right). It is notable that in-house research and development preceding these products may have started about 5 years earlier. In a similar way, smaller start-ups have directly taken over prototypes and engineered them into on-demand, small-scale production [41, 42] or built on their patented technology [43]. For example, Touchtech AB of Sweden develops novel tabletop solutions for fairs, stores, and offices. These solutions often also include a suite of tailored software and a software API for developing multi-touch applications.

Tabletop Trends

The research domain and community around tabletop systems was established in the early 1990s and has since developed steadily. Then, in 2006, an annual international workshop (now a conference) was established to serve as a formal forum for this research. It began in Adelaide, Australia, then headed to the USA, Europe, and finally to Canada. Initial government-sponsored research programs and laboratory research carved out early tabletop research directions such as distributed collaboration [18, 58], tangible interfaces [12, 15] and collaborative interaction at the tabletop [44, 13]. Since then major companies have developed and commenced selling tabletop products, indicating that the research domain and its technologies have matured enough to be a prosperous and profitable business. At the same time, mainstream media visibility of tabletop systems and applications has grown consistently since 2005. All these observations may signal a completion of technology transfer from research labs to industry. From now on, companies and their research departments will develop and refine products for broader end-user communities. This phase of product development may ultimately lead to a stable economy of a yet unknown volume, as demonstrated by inventions such as the GUI, the PC, and the Internet [56]. This phase may last another decade until the market has reached a sustainable volume.

Trends in Research

When the industrial development of tabletop systems started, the research community extended the focus of their conference from tabletops to "tabletops and interactive surfaces." This may have been done to address a broader scientific audience and partly to enlarge the research community. However, it can be observed that other conferences with related topics, such as the recently launched International Conference on Tangible, Embedded, and Embodied Interaction (TEI), might overlap with this extended topic. This observation also indicates the trend that new directions may be required to maintain a viable and innovative field of research. Novel directions are important to maintain interest and attract government funding, which restarts the cycle of investigating a broad set of ideas that, in turn, trigger the development of new commercial products. By now, the research area of multi-touch interaction on large display surfaces has demonstrated its potential to be a driving force in the creation of new prototypes and systems. It has the potential to stimulate a new range of exploratory research and embrace novel technologies as yet unknown. New opportunities may arise from novel form factors of displays and cost-effective production of multi-touch device technologies. Outcomes in these areas have the potential to refuel the development and redesign of tabletop products.

Since the 1990s the investigation of TUIs has been on the research agenda of Hiroshi Ishii. New research into tangibility has recently arisen from the affordance of horizontal tabletop surfaces in the same manner that multi-touch research evolved from single touch interaction in tabletop systems. This research trend is even followed in ubicomp scenarios where users interact with an ecology of artifacts, that is, in an environment augmented by various devices such as mobile phones and digital cameras, as well as laptops and netbooks. In that sense, tabletop research bears the potential to unify various interaction and interface paradigms in the concrete scenario of co-located collaboration of a small group around an interactive table.

So far, user studies with tabletop systems have been conducted predominantly in labs and controlled environments. When systems become affordable and available, thus finding their way into the real world, new research opportunities may arise. Researchers might, for example, run longitudinal studies on the adoption of this new collaborative interface and its impact on work processes, social interactions, and domestic activities.

Trends in Enabling Technologies

Novel display technologies tend to influence the physical design of tabletop systems. A transition from data projection systems to direct displays such as LCDs is occurring. Display manufacturers present future trends at technical fairs by showcasing prototypes with extraordinary characteristics such as Organic Light Emitting Diodes (OLEDs). These can form displays that are flexible and bendable compared to the rigid construction of LCDs, and, at the same time, OLED displays are significantly thinner than both LCDs and PDPs [25]. It is predicted that OLED displays can also be produced more cost-effectively. Using a similar technology as that which is used to print ink on paper, OLEDs can be printed so as to constitute a display. So far, OLED technology has been used and deployed for small-sized displays, but it is a matter of time before larger displays become available. The consequences for tabletop systems are not completely foreseeable, but a thinner display basically allows augmenting every existing horizontal surface without compromising the design of the supporting table. This rising technology is driven by the demand in the consumer electronic market for large and thin home television sets.

Combining OLED displays with thin multi-touch devices are the next step towards the ultimate tabletop system, but these new technologies have yet to be fully developed. Recent research has presented new, cost-effective methods of producing multi-touch devices [22, 23]. The physical form factors of these touch sensor matrices match up with those of OLED display matrices, while at the same time efficient production seems conceivable. Alternatively, projects such as Thinsight and MightyTrace aim to reduce the bulkiness of current systems by replacing the infrared sensor with an array of discrete sensors that allows for a lower profile [54, 55]. The ultimate goal of these efforts is the convergence of the touch-sensing device and a thin, flexible display matrix into one integrated element that can be efficiently manufactured at a large size of 40 inch (107 cm) or more.

Optimal hardware set-up is a key challenge to the practice of tabletop system design. Another challenge will be the development of an appropriate application and software environment to leverage on the advanced hardware technologies. The development of new software technologies seems to require a longer incubation time than hardware.

To date, modern computer operating systems as well as standard applications such as text editors and spreadsheet programs are single-user applications. On interactive tabletops the applications have always been dedicated software developments or research prototypes. However, in order to facilitate and simplify building genuine tabletop applications two requirements must be fulfilled. Firstly, multi-touch input devices must become standardized in accordance with other peripheral interaction devices such as the mouse, keyboard, and single-point touch screen, which operate and communicate with applications regardless of the manufacturer. Secondly, standard operating systems must be extended or modified to handle specific multi-touch and multi-user input events. Like in tablet-PC editions, *multi-touch editions* of popular operating systems may become available as commercial or open source products. The fulfillment of these two requirements would allow a larger user community to experience interactive tabletops.

The demand for multi-user support originates from research into collaborative group work, and the requirements of multi-touch and multi-user interfaces resemble those of Single Display Groupware (SDG) as described by Stewart et al. in 1999 [59]. While discrete interactions such as clicking a button or lifting the finger from a button may be simple to handle in multi-user applications, more continuous interaction requires rethinking interface widgets, such as scroll bars and sliders, to avoid interference [60] and improving groupware interface via so called coordination policies [61, 62]. Ultimately, the operating system should register and trace the identity of users in order to allow for individualized input commands. The capability of identifying the originator of a touch event has been realized in the DiamondTouch system [6], but this has not been addressed by later projects.

There is a tendency to pursue a more moderate strategy for introducing multi-touch features. It has become popular to support a single user's hand gestures by mapping them into the traditional event processing of a computer system. Examples include a dual-touch sliding gesture used to scroll and a pinching gesture to control the zoom feature. While providing new features for the user, this development approach is rather moderate since it is based on the PC paradigm and does not require the substantial modifications of the computers operating system to provide multi-user input event processing [63].

Trends in Commercial Products

In the near future we expect affordable commercial products to be introduced in shops, public spaces, and the educational environment. Tabletops may also come to be bought for laboratory studies as alternatives to specialized experimental set-ups. Since the development of a comprehensively and continuously supported product requires a long period of time, there is a potential for small companies to emerge. Large-scale production of a tabletop system may require standard solutions, hindering the fast adoption of new technology and allowing only smaller improvements. Hence, younger companies tend to be better poised to adjust to and integrate late-breaking technology into their production line. We are currently witnessing this diversification in the commercial domain and in the future the consumers will have the choice to buy either fully developed products or one of a kind, specialized products employing cutting-edge technologies.

Discussion and Summary

We have presented a short historical overview of more than a decade of research in the area of interactive tabletops, enabling technologies, and commercial products. In doing so, we have described the phenomenon of interactive tabletops as an example of how innovation and technologically oriented research in the domains of HCI, CSCW, and Ubicomp may turn into a prosperous business. We have pointed out that an incubation period from early research works to stable economy may be up to 30 years. Current product lines from major companies mark the completion of technology transfer from research labs to the industry. However, it may take another 10 years until the business becomes sustainable. We have exemplified how government-sponsored research in various countries has played a significant role in the early periods of this history. Also, we have shown how the various enabling technologies, such as displays and touch sensors, were and still are important factors for tabletop systems. The direct and unobstructed experience these technologies offer may, to some extent, explain the general fascination with them throughout research and end-user communities.

Based on our review of research, technologies, and products, we have identified and traced three transitions in terms of research and development caused by innovative systems and applications. The first transition, from lab prototypes to real world collaborative applications, was motivated by the research questions of the CSCW domain. The second transition, from single touch to multi-touch and tangibility, can be associated with the research domain of HCI. The third transition, from projection to direct display technology, was stimulated by recent advances in consumer electronics. For each of the transitions traced and visualized in the synoptic landscape, we imposed a saddle point nearby landmark publications and products.

Finally, we presented plausible and foreseeable trends which may spur transitions in tabletop research and affect future user interaction. Looking back on more than a decade of activity, tabletop research has reached a certain level of maturity. This activity has led to the establishment of tabletops as a valid alternative to PCs and interactive whiteboards as a tool for collaboration in small teams. However, successfully integrating tabletops into the current practice and culture of our work places as well as in the public and domestic spaces is still on the agenda.

Acknowledgments We are greatly thankful to Erik Tobin who helped in making the text more enjoyable to read.

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