Human Computer Interaction, foundations and new paradigms

Alan Dix

University of Birmingham and Talis

Abstract

This paper explores the roots of human computer interaction as a discipline, the various trends which have marked its development and some of the current and future challenges for research. Human–computer interaction, like any vocational discipline, sits upon three broad foundations: theoretical principles, professional practice and a community of people. As an interdisciplinary field the theoretical roots of HCI encompass a number of other disciplines including psychology and computing, ergonomics, and social sciences; however, it also has theoretical and practical challenges of its own. The evolving internal and external context of HCI computers have become smaller and less costly, this has led to changes in nature of the users and uses of computers, with corresponding impact on society. The paper explores the current challenges of computers from the cloud to digital fabrication and the need to design for solitude. It suggests that HCI can not just react to the changes around it, but also shape those changes.

Keywords

human–computer interaction; history, ubiquitous computing; cloud-computing; design for solitude; digital fabrication

Introduction

From 'foundations' to 'new paradigms' is a wide canvas and this paper attempts to paint a picture of human–computer interaction from its earliest roots to future challenges. It is also iconic in that HCI as an academic discipline has always been positioned, sometimes uneasily, sometimes creatively, in the tension between solid intellectual rigour and the excitement in new technology. Stefano Levialdi, in who this special issue is in honour, had a rich appreciation of both and so I hope this paper is one that he would have enjoyed as well as offering an overview of the field as it was, as it is and as it could be.

Foundations

Human–computer interaction, like any vocational discipline, sits upon three broad foundations.

Principles – First, and most obviously are the intellectual theories, models and empirical investigations that underlie the field. Give HCI's cross-disciplinary nature, some of these come form a number of related disciplines and some as core HCI knowledge.

Practice – Second, HCI is a field that, inter alia, seeks to offer practical guidance to practitioners in interaction design, usability, UX, or whatever becomes the next key term. However, also it is a discipline that has always sought to learn form the practical design and innovations that surround it.

People – Finally, there are the visionaries who inspire the field and perhaps most importantly the HCI community itself: researchers, educators and practitioners.

I will not attempt to separate these three in the following sections as they are all deeply intertwined in both the history and current state of HCI.

The interplay between the first two is central to the long-standing discussion of the nature of HCI originally posed by Long and Dowell [LD89]: is it a science, engineering or craft discipline? However, when I addressed the scientific credentials of HCI in my own response to this work [Dx10] in the IwC Festschrift for John Long, I found myself addressing as much the nature and dynamics of the academic community as the literature itself.

I will not reprise the arguments here, but the importance of the community is a message that is also central to Stefano's legacy. As well as deeply humane person at a one-to-one level, his contribution to the development of the Italian HCI community, and the founding of the AVI conference series have been of importance to many individuals as well as the academic growth of the field. It is not that the archival written outputs are not critical, indeed Stefano's role in JVLC is evidence of that, but that scientific outputs are always the result of a human process.

Historic Roots

HCI developed as a discipline and a community in the early 1980s, triggered largely by the PC revolution and the mass use of office computers. It was in the early 1980s when the major HCI conferences began Interact, CHI, British HCI and Vienna HCI; all but the last still active today. Core concepts were also formulated in those days including the notion of direct manipulation and user centred design [Sc83,ND86].

However, while the identifiable discipline began in the 1980s, the intellectual roots can be traced back at least 25 years earlier.

The graphical user interface and desktop metaphor, embodied in the early Apple Mac, were the result of work at Xerox PARC throughout the 1970s, mostly based around graphical programming environments such as Smalltalk and InterLisp, and leading to the design of the Xerox Star office computer [SK82, JR89], a conceptual breakthrough albeit a commercial failure.

Going back further, Sutherland's Sketchpad [Su63], the first graphical user interface dates back to the early 1960s and in the same period, Englebert's 'research centre for augmenting human intellect' was responsible for the invention of the mouse, as well as early versions of electronic conferencing [EE68].

However, the very first true HCI paper dates back into the late 1950s, with Shackel's *'Ergonomics for a Computer'* [Sh59]. While Sutherland and Englebert were early examples of the vision/innovation side of HCI, Shackel's first HCI paper came more from a practical design perspective, the redesign of the control panel of EMIAC II, an early analogue computer.

Although the computer was analogue not digital, and the controls knobs and patch-panels, not mice or keyboards, many of the principles of practical usability engineering can be seen in this very earliest HCI paper including prototyping, empirical testing, visual grouping, and simplifying design. Furthermore this very practical work rooted itself in earlier theoretical work in ergonomics and applied experimental psychology, in many ways prefiguring the discipline we know today.

Theory and Contributing Disciplines

As already noted, the theoretical and empirical foundations of HCI draw partly from a number of related disciplines and partly are special to HCI itself.

In the earliest days the main disciplines involved in HCI were computer science, psychology and ergonomics, as reflected in Shackel's early paper. However, these disciplines were soon joined by social science, or, to be more precise, the ethnographic and anthropological side of sociology.

The input from ergonomics was initially in terms of physical ergonomics, sitting at a computer terminal, pressing keys; however, this more physical side of HCI declined rapidly as computers became commoditised as opposed to being in special settings and issues of physical ergonomics were relegated to health and safety concerns. To some extent this followed from the natural development of the area, once computers were mass-produced, practitioners had little control of the physical system unless they worked for major manufacturers. However, users have suffered from this loss of ergonomic input: many laptops and other devices sacrificed physical ergonomics for surface aesthetics, as a generation of RSI sufferers will attest! Happily, in more recent years, issues of physical design have resurfaced with interest in tangible computing and strong research connections developing with product design.

Another disciplinary connection that waned but is resurfacing is that of broader socio-technical design. Certain practitioners and researchers drew in the work of information scientists such as Enid Mumford [Ri06] and Checkland's soft-systems methodology [CS99]. While this has had its legacy in HCI theory and practice, not least the focus on multiple stakeholders, the fields of information science and HCI have been largely parallel rather than interconnected except in the Nordic HCI tradition.

However, as with the physical side of HCI, there are signs of resurfacing interest in more organisational or community focused views of human activity. This is perhaps most marked in the related web science community where methods such as social network analysis are clearly very important, enabled by the vast quantities of data obtained form web-based systems. However, these techniques are also being used within HCI, not least Liu et al.'s study of HCI itself [LG14], which we'll return to later.

A few years ago Clare Hooper and I looked at the relationship between HCI and web science [HD12, HD13]. Although there are core differences in scope and focus, there are strong overlaps between the two. We drew on the web science 'butterfly', which includes all the disciplines that web science draws on. This was remarkably similar to those that connect with HCI differing mostly in the 'heat map' of those most active or relevant (see figs 1 and 2).

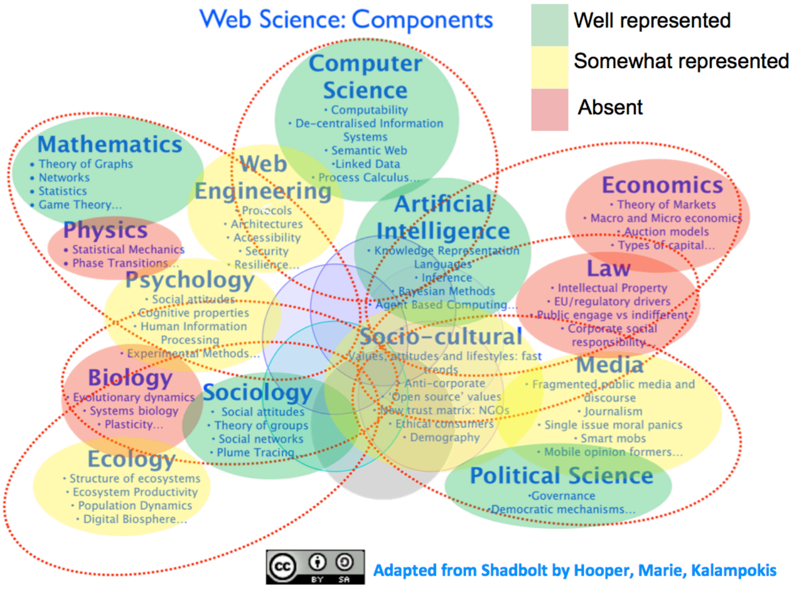

Figure 1. Web Science 'heat map', showing discipline presence [HM12]

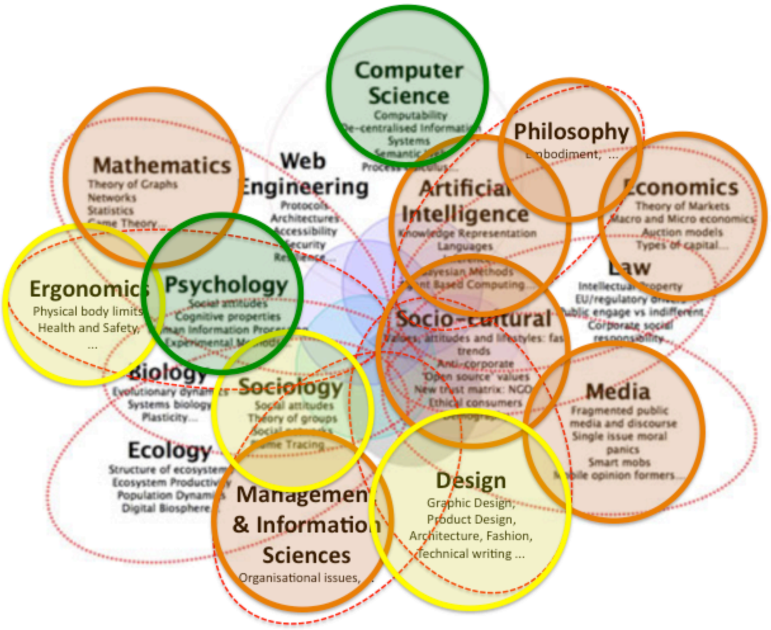

Figure 2. Heat map for HCI (from [HD13])

Borrowings from other fields have been very powerful to enable both theoretical and practical interventions. For example, Fitts' Law [Fi54] has created its own small sub-community, human–human conversation analysis has been used to design human–computer dialogues [FL90], and Csikszentmihályi's concept of Flow [Cz90] has proved influential in user experience design.

However, while HCI can draw on the methods and knowledge of related fields directly, there are limits to this for two reasons:

different concerns – The questions we ask in HCI are typically more applied and hence more complex in terms of interrelations than 'base' disciplines, notably psychology. For example, early studies of on-screen reading comprehension, or more recent comparisons of reading comprehension when holding a screen vs with hands on the table [BJ11]; while in many ways these could be seen as standard perceptual and cognitive psychology, the reasons for studying both were practical and unlikely to have arisen purely from a psychological interest.

integrating knowledge – Some concerns really cut across disciplines requiring theoretical or practical knowledge from multiple areas of study. For example work on how design affects behaviour [PV15], requires both behavioural psychology and interaction design.

However, while there is copious empirical work of this kind, it is harder to find truly integrative HCI theory. There were early descriptive accounts, notably Norman's seven stages of action [No86,No88], and more predictive modelling approaches such as Card, Moran and Newells' 'Model Human Processor' [CM86] and Barnard's 'Interacting Cognitive Subsystems' [Ba85], but, while the former is still influential, there is no clear path of deepening theory of interaction.

Liu et al. [LG14] used co-word analysis techniques to investigate the development of themes and bodies of knowledge in HCI. This showed positive things, notably the level of cross cutting integration across the field; that is there are no disconnected camps. It also gave evidence to known effects such as the way that new technologies seem to buffet the discipline starting new themes, which rise for a period before trailing off. However, it also exposed a concerning dearth of integrating bodies of knowledge:

"*As it stands, the only tradition in HCI is that of having no tradition in terms of research topics. ... when a new technology comes along it seems that researchers start from scratch leading to relatively isolated research themes*" [LG14]

Human – technology interaction

One of the more recent changes in HCI is that computers really have become ubiquitous to the extent that it is rare to find any technology that does not involve computation, and if not in the artefact, in the design process, ordering, or manuals. This process began some time ago. In the mid 1990s I met appliance designers attending HCI conferences because they were beginning to have computer control panels and so they needed to understand interaction design principles. The difference is that at that stage computers were just beginning to be embedded in domestic technology, whereas now the two are almost synonymous, from heating radiators you can control from your mobile phone to QR codes on paper posters.

So human–computer interaction is now effectively human–technology interaction.

This creates new challenges for the discipline, but also opens up a longer history of human innovation and evolution of technology. That is in understating the foundations of HCI we can draw on millennia, not just the mere thirty to fifty years of digital development (rich and rapid that it has been).

Ogburn and Gilfillan [OG33] were some of the earliest modern historians of technology, and in the 1930s were reflecting on recent decades, which would have seemed as revolutionary as our own (fig. 3). They, and more recent commentators such as Basalla [Ba88] and Arthur [Ar09], emphasise the continuity of technological change in contrast to what are often described as 'heroic' theories of invention focusing on great individuals.

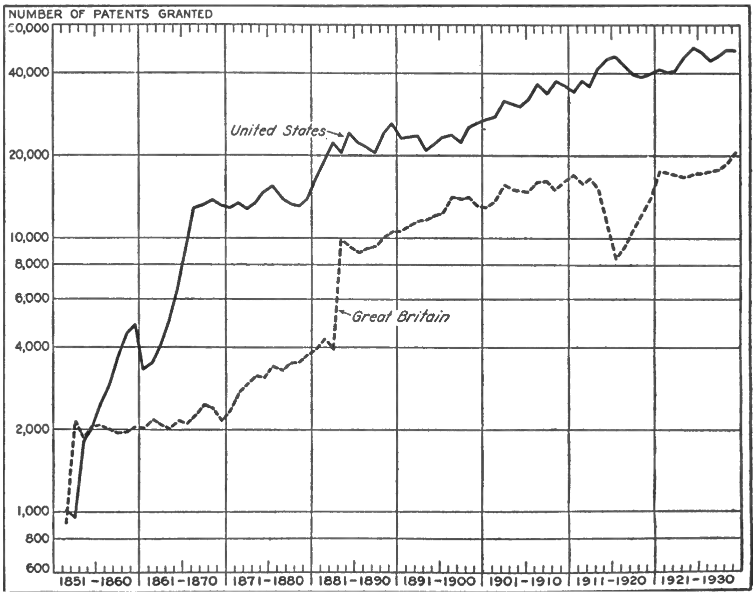

Figure 3. Growth in US and UK Patents 1852-1930 [OG33].

However, this does not mean that the social ramifications of these inventions are not significant. Reflecting on medieval technological change, White [Wh66] argues that the invention of the stirrup not only radically altered warfare, but its effects rippled through to agriculture (because of the breeding of large horses which the replaced oxen) and fundamentally changed the social order as the feudal system developed to create units capable of 'servicing' the horsed knight.

Interestingly, from a digital perspective, when looking at early 19th century inventions, Ogburn and Gilfillan [OG33] focus on telephony and radio as an 'example' to demonstrate the widespread potential changes wrought by technologies. They list 150 effects including many that seem familiar today when we look at the impact of the web, both those that seem more positive (e.g. "*Distinctions between social classes and economic groups lessened*") and possibly negative (e.g. "*Regional differences in cultures become less pronounced*").

At a more practical level, Alexander's concept of 'patterns' [AI77, Al79], itself reflecting on the lessons of past architecture, has been adopted in HCI to reason about user interfaces [Ba01, DF06].

Looking back further still, there are arguments that human cognition developed in part due to a sort of co-evolution with technology; for example, Calvin [Ca91] argues that the development of the stone axe as a throwing weapon developed both manual dexterity that enabled future tool development; and, in the end more importantly, mental sills for fine sequencing that enabled language and logical thought.

While this sounds far from current HCI, we should consider Fitts' Law [Fi54], which states that the time taken to move to a target (such as moving a mouse to select an onscreen button), is proportional to the log of the ratio of distance and target size. This has been one of the enduring and most celebrated uses of basic psychological theory in user interface theory and design, from its incorporation in Card, Moran and Newells 'Model Human Processor' [CM86], to ISO 9241-9 [IS00] and seemingly innumerable conference and journal papers [SM04].

Most work on Fitts' Law is empirical however, it can also be viewed as an outcome of the cybernetics of the human body, as the small but finite time it takes for visual stimuli to be processed leads to a iterative corrections of an initial 'ballistic' movement [Di03]. However, in contrast to this, psychological results on eye movement data suggests that saccades are essentially independent of target size [Dr10]. This is because, once the object of attention lies within the fovea, it is visually distinct enough for most purposes, so our eye muscles have developed to be accurate enough to do this without correction.

While the eye is somewhat special as other hand-eye motor coordination (whether arm, finger or foot) depends on the eye first acquiring the target, in fact if you focus on a point then close your eyes, you can move your hand to cove the point almost every time without corrections. Similarly if you place your hand within finger reach of a dot, and again close your eye and try to touch the dot with your finger, you can do this with high accuracy. Fitts' Law seems to kick in when the size of the target is smaller than the size of the 'effector' (hand or finger tip), that is we can do 'normal' bodily physical movements with high enough accuracy.

Fitts' original experiments were with a stylus and HCI experiments are almost always with some sort of artificial cursor. That is Fitts' Law is a law of the artificially (or cybernetically) extended human body. The wonder is that we can control such devices, but this is because the earliest Homo Sapiens were tool users; we have always been cyborgs!

Continuity and and Change

In discussing the foundations of HCI, we have already seen some changes and trends. In this section we look more systematically, if not exhaustively, at some of the changes in HCI itself and the technological context within which the discipline operates.

How many?

It is often said that in 1953 IBM believed that there would never need to be more then five computers in the world. While this turns out to be a misquote (see footnote 8 in [Dx10]), it is still true that in the early days the room-sized computers were envisaged as something that would only be needed by very large organisations. In this light, the decision, even in the late 1970s, to use 32 bit IP addresses [Po81], nearly one for every human being in the planet at that time, appears prescient.

> *"It would be easy to say the modern car is a computer on wheels, but it's more like 30 or more computers on wheels"* [Mo10]

Of course, there are now far more than 4 billion people on the planet and mobile phones alone (each with a computer more powerful than the 1953 IBM 701) outnumber people [Bo14]. After many years, IP v5 is being fully deployed, with 64 bit addresses allowing 2 billion addresses for every human being on the earth, or enough for more than ten computers on every square centimetre of the earth's land mass.

As well as being big numbers and creating new challenges for network routing, this scale changes the nature of HCI. Although we have sketched the origins of HCI onto the late 1950s, the discipline was formed with the rise of the desktop PC, one computer per person, the age of IPv4. As we contemplate thousands of computers per person, it is not clear that the old metaphors hold. This is partially the fulfilment of Weisier's vision of ubiquitous computing [We91], but partly going way beyond in terns of scale, both large and small.

In 2004, Jo Finney and I developed Firefly, which puts a separate computer behind individual LEDs [CF09]. An early demonstrator was a small Christmas tree with several thousand single-pixel networked computers wrapped round it. While Weiser talks about displays at yard, foot and inch scale [We91], this is at a far smaller, 'poppyseed scale' [DS10]. While this scale is still rare, it is common to find dozens of computers in a single car [Mo10], and NFC tags are found in commercial packaging, so a typical shopping bag could contain many simple computers. Adam Greenfield calls this phenomenon of commoditised computation 'everyware' [Gr06].

Weirdly, just as computers have shrunk and proliferated, there is also a counter move to recentralise. While the internet giants are not operating single computers, a significant proportion of the world's computation, and certainly network traffic, happens in a handful of corporate distributed server farms.

Who?

In the early days of computing, the 1960s and 1970s, before HCI emerged as a discipline, computer users were of two very different kinds. The creators of software (programming and design) were mid-level employees, and relatively well educated, although even then split very much between those involved in the design and creation of computers and operating software, and those involved in business programming. In contrast the *direct users* of computer software were often low level, low paid, and involved in relatively repetitive jobs such as data entry. The dominant professional interest in this was concerned with physical ergonomics, a Taylorist desire to ensure that workers were as productive as possible.

In contrast, the desktop PC radically changed the nature of the end user, shifting to professional, clerical, and middle management and, to some extent, more creative and intellectual work. The development of HCI is usually seen as the reaction to this more individual form of computation. Alternatively, more cynically, this could be seen less a humanist agenda and more to do with the changing costs between computer and user: a shift from cheap labour using expensive computers to cheap computers used by expensive employees.

The new millennium, and not least the rise of the web, has meant that now the end user is everyone.

Of course, this is still a slightly idealised view. Currently less than half the world's population has access to the Internet [IG15] and that proportion is heavily weighed towards developed countries. The core barriers are economic and educational, but design plays a part hence the continuing importance of the ICT4D (ICT for Development) agenda within HCI [DD12]. Crucially, this should not be a one-way street with 'clever HCI people' helping those who are less able [RM13], but a process of mutual learning and enablement [DS10b].

Even in developed countries the best access tends to be focused on the more affluent and able. This is emphasised by the changing demographics of many developed countries in many of which the retired population is expected to outnumber those in work. These aging populations will increase the need for user interfaces and systems that continue to function even as human perceptual, physical and mental function degrades. The ASSETS community has long served those who by birth, accident, or age do not share the same abilities as the 'norm', the work in this area was always important, but will grow more so.

During my thousand mile walk around Wales in 2013, it was rare to find even usable GSM mobile signal, let along 3G which was only accessible in major cities [MD14], and during the walk a Welsh government report found that 50% of schools said that poor Internet connectivity was hampering education [Es13]. However, it is not just rural areas, which suffer; a report commissioned by the Royal Society of Edinburgh showed that internet bandwidth was strongly correlated with other measures of social depravation [FA13] – digital technology widens existing social divisions.

Some of the issues are about government policy and economics, but as a community we cannot simply wait for social change. Interface and digital design makes a difference, sadly often for the worse. In the first journal paper on HCI issues for mobile systems [Dx95], I looked not at issues of screen size, but intermittent connectivity. Twenty years later, walking the margins of Wales, it was poor design for low connectivity, not the low connectivity itself, which was often the main issue: major software failed in predictable and avoidable ways [Dx13].

The challenge for HCI is to really ensure we design for all.

Of course even if everyone can use software, those who can create it are few – the gap between programmers and users is nearly as large as it ever was. Of course, part of being a large-scale consumer society is that may of the things we use are beyond our skills to make or even modify – when a plastic spoon breaks you throw it away, when your car breaks down, you call for a mechanic.

While computers were something one used occasionally, this argument perhaps seemed valid; however, when everything is controlled by computers and is interlinked, the ability to be able to understand and modify, at least to some extent, becomes more important. That is, general computer literacy and end-user programming move from being marginal interests to centre stage. Stefano had a long interest in visual languages (hence this journal). These may be used for sophisticated purposes, but often lie behind some of the most widely used educational and end-user programming systems (e.g. Scratch, Max/MSP).

Tommaso Turchi , one of the PhD students of one of Stefano's ex-PhD students (Alessio Malizia) has been working on tactile as well as visual languages for end-user programming, and furthermore has been working with me to see how this could be used in a small island community; that is, bringing together both aspects of this section [TM15].

What for?

Along with the change in users, those who have been in HCI since the early days have seen a dramatic change in the *purpose* of the systems being developed.

In the early days, from the first computer systems through to the focus on desktop PCs in the 1980s, and CSCW in the 1990s, the focus was on computers for work. This was sometimes realised in more Taylorist forms of task analysis [DS04], sometimes in more interpretative ethnographic studies [Su87], sometimes in more democratic participatory approaches [Gr03, MK93], but the aim was principally to help make work more productive, and possible more enjoyable too (especially if that made it more productive). While 'satisfaction' was always part of the early definitions of usability, it was almost always in f efficiency and effectiveness which took centre stage.

Although work-centred systems are still important, a key change in HCI was when computation entered leisure and home-centred systems. The market for social networks, satellite navigation, smart phones and smart TVs is no longer the corporate buying for its workers, but consumers buying for themselves. This shift from *employer-determined* to *self-determined* choices of systems drove in no small part the shift from efficiency and user interface design, to emotion and user experience design.

However, we are in the midst of another shift, perhaps equally profound. The ubiquity and (near) universality of internet access means that many common services are becoming largely or solely online access. Many goods are cheaper if purchased online, airlines often expect that boarding passes are downloaded and printed before arriving at the airport, music and movies are streamed. In the face of budget cuts the BBC is moving several broadcast channels to be digital only, and many expect that printed news media will eventually disappear. Furthermore, in many countries government and heath services are increasingly online.

That is, the very *structure of life* is increasingly computational and networked, and this is not optional. For example, in the UK welfare payments are being moved to a new system of 'universal benefits'; this change is being accompanied by a shift to wholly online access – for those, who by definition, are likely to be poor and less well educated. We are moving form the era of *self determined* computation to one that is *societally determined*.

The social problems with this are clear from the preceding section. As a discipline HCI may likewise need to shift as we move from a decade that that was based on free choice and therefore focused on users as consumers, to one where there is a little choice, and users are citizens.

Drudgery and Creativity

Englebert's ground breaking 1960s research centre was aimed at "*augmenting human intellect*" [EE68] and Vannevar Bush's 1945 vision of MEMEX, often seen seen as the origin of hypertext, was to make the collective knowledge of human kind available for the good of all [Bu45]. More generally, utopian views of automation see it as removing the drudgery of repetitive work.

For computers the critical shift was not so much utopian as economic. The earliest end users spent their time feeding the computer, largely because the computer was expensive and they were cheap. However, as we discussed earlier, as computers became cheaper and in higher volume, there came a point when it as worthwhile making them serve people and HCI was born.

Within HCI, the issue of function allocation, which jobs belong with the computer and which with the human, is constantly evolving as technology redefines the boundaries of what is better done manually or automatically. In an aircraft cockpit this boundary may shift dynamically depending on the pilot's workload; visualisation techniques seek to exploit the power of computation to present data in ways which exploit the visual pattern seeking abilities of humans; even the humble word processor reflows text as the human writer composes the words.

However, the lessons of history show that the utopian image of technological development is rarely simple. The Luddites of the 19th century are now seen as the epitome of backwardness, fighting the (inevitable) change to more efficient and productive textile mills. However, examinations of the writings of the time showed that for the mill owners automation was more about control than efficiency, shifting a previously independent and self-employed industry into a centralised one based on employment and coercive working hours [Th63].

It is very unclear where recent developments such as Uber fit into this picture: enabling individuals to connect and increasing autonomy, or making them cogs in a machine.

These issues are playing out within HCI and related areas, so we have the potential for real impact. The area of human-computation is often about fun games such as image matching, or minor task-related activities such as reCaptcha codes [AM08]. Typically the humans engaged in these tasks have little or no idea of how their small intellectual labours contribute to the overall goal of the system (e.g. improving OCR) – a clever balance utilising the power of the human intellect, or treating people as components? Large-scale systems such as the way Google uses statistics on page popularity, or Amazon recommendations are not commonly described as human computation, but effectively are just that, and Web Science is sometime described as the study of 'social machines' [HB10].

In 1842 Ada Lovelace wrote of the Analytic Engine, "(it) *has no pretensions whatever to originate any thing. … Its province is to assist us in making available what we are already acquainted with.*" [Lo43]. That is, she saw it, very much in the same light as Englebert did, augmenting human intellect. In contrast, there is growing serious discussion of 'the singularity', when artificial intelligence designs itself [Vi93, IE08].

The latter may seem somewhat theoretical, but in HCI we constantly face this tension between technological determinism and human capabilities. A good example of this was in the recent UK REF exercises, evaluating all UK university research [RE14]. The computing sub-panel used an automatic algorithm to normalise the different grading patterns of reviewers (some more generous than others, some more central markers, some marking to extremes). This sounds reasonable, except that in order to get the algorithm to work 'optimally' there needed sufficient overlap between reviewers' paper allocations, and in order to achieve that overlap reviewers 'spread' their expertise, reviewing works far from their core areas [Di15]. That is, in order to 'optimise' the machine algorithm, the role of human expertise was diminished and the whole human–computer system compromised.

To some extent this is such an obvious socio-technical error, and yet this happened in the context of some of the most eminent computer science academics in the UK. The human–computer processes we find around us today are often far more complex. As a discipline and a community in HCI, we need to develop the tools and techniques to understand and design such systems, and equally important be able to communicate this to others.

Formalism and architecture

My own earliest discussions with Stefano concerned the formalisation of interaction [DM97, DM97b], and this was also my own roots in HCI [Di91], so it seems appropriate to look at the arc within HCI of the more formal and engineering aspects of the discipline.

Some of the early work in HCI involved forms of mathematical modelling, not least the Model Human Processor [CM86], often drawing in cognitive science roots influenced by AI. These more reductionist models were challenged in the early years by Winograd and Flores' "*Understanding Computers and Cognition*" [WF86] and Suchman's "*Plans and Situated Actions*" [Su87], and led to a widespread distrust of more formal methods in HCI ever since.

Despite this there has been a small but active community in formal methods for HCI, initially focused strongly around the York group in the late 1980s and early 1990s, and continuing since in a number of specialists conferences, which eventually merged to become ACM EICS. There have been a number of collected volumes over the years [TH90, PP97] and a 'state of the art' Springer volume is imminent [WP17].

The mainstay of this work has tended to be researchers and practitioners working in safety critical environments such as air traffic control. However, as we have seen, a number of trends are moving towards larger numbers of simpler components working together (from apps on a smart phone to myriad ubiquitous devices). The new complexity is likely to be in the interactions between these many simple components; just the sort of issue that it is often hard to conceptualise intuitively, but well suited to formal analysis. There is a real opportunity for work in this area.

Another strand of HCI work, which has had a similar arc to formal methods, is the engineering of user interfaces including tools, toolkits and architectures. This was important in the early days of HCI notably the development of the Seeheim model [PH85], MVC [KP88] and PAC [Co87]. This has continued to have a core community represented in IFIP WG2.7 and ACM EICS, but also periodic more widespread work as new kinds of technologies emerge and architectures needed, for example, work in the early-2000s on event architectures for ubicomp (e.g. Elvin [LR00] and ECT [GI04].

Currently practical user interface development is often focused around web applications and in this community there is active work on frameworks and architectures, often based nominally around MVC (although sometimes closer to PAC in practice). There does not seem to be a corresponding body of HCI research work either feeding into these developments, not learning from them, another potential area for increased effort.

Visualisation

Visualisation was another core area for Stefano, and one of ongoing importance as data continues to multiply. Indeed there is now more data created in the world every second than there was in a whole year in the early 1990s [Wa15]. Although there had been work in scientific visualisation and graphics before HCI existed, it was in the early 1990s that the speed of graphics terminals made interactive visualisation possible and spurred a period of innovation not seen since (for example, Cone Trees [RM91], TreeMaps [Sh92], Pixel Plotting [KH02], Starfield [AS94] and Shneiderman's visualisation mantra [SP10]). However, the sheer volume of data has led to new challenges over recent years, in particular the rise of visual analytics combining visualisation and various forms of automated analysis such as data mining [TC05, KK11]. It is likely that the Big Data agenda will continue to push research in this area for some time to come giving rise to interesting and important user interface challenges [DP11].

While some data is proprietary there has been a huge growth of Open Data especially government data, offering the potential for third parties to interrogate data and potentially use it to challenge policies and engage in democratic debate. This has enabled a new media area of data journalism [GC12], for example, the Guardian datablog [Gu16]. However, as with end-user programming, the ability to harness this data is far from universal. Those that are most easily able to afford the skills and processing power to benefit from open data are often those who are already most powerful. There is a real challenge for HCI to make large-scale data visualisation and analysis usable by small-scale communities and interest groups [Di14].

Intelligence and autonomy

Artificial intelligence (AI) was influential in the earliest days of HCI; indeed 'Norman and Draper's User-Centered System Design [ND86] was precisely founded on a collaboration between cognitive science and AI. One side of this, already discussed under formalism above, was the use of models of cognition drawing on AI understanding. The other side was the more practical use of AI techniques in the development of intelligent user interfaces including Alan Cypher's early work on programming by demonstration [Cy91]; this work has continued, not least in the annual IUI (Intelligent User Interfaces) conference series. After an early period of high expectation, and possibly due to a level of overhype, for many years the area has sometimes been regarded as somewhat simplistic in mainstream HCI. Even during this period practical aspects of AI have found theory way into user interfaces including vision, speech and handwriting technology. More explicit use of AI has also been a part of context-aware systems, both in physical, ubiquitous systems and also virtual systems such as Cyberdesk [WD97]. However, it has been the advent of large-data, big-data and cloud-computing machine learning, which has really brought AI back into the forefront of user interfaces, for example, recommender systems such as Amazon's almost uncanny ability to suggest potential books to read.

Halevy et al. based on experience in many areas at Google, have written about the "unreasonable effectiveness" of big data. In particular, areas that were once the purview of symbolic AI techniques, such as natural language processing, being tackled by large-scale statistical and machine learning algorithms [HN09].

Many years ago, in the early days of the use of non-symbolic AI such as neural networks, I wrote about some of the challenges these raise for the transparency and accountability of computer systems [Dx92], including examples of then potential for implicit sexual and racial discrimination. Although it has been a long time coming, these very issues have come to the fore with complaints that Google image search produces gender-biased results or the Microsoft chat-bot that learnt (from humans on Twitter) to use racist language [Hu16].

Some of these issues need to be tackled by AI and machine learning researchers at the level of the algorithms, but in HCI we need to work with them to understand better the ways to present and manage the results of 'black box' algorithms, so that they are either comprehensible or at least not problematic when they go wrong, a process I have called 'appropriate intelligence' [DR00].

Agency and Physicality

Finally in this section we will look at issues of agency (connected to intelligence) and physicality. While these seem very different, their arc in HCI has been closely linked.

One of the core developments in early HCI was the rise of the graphical user interface GUI) and direct manipulation [Sc83]. The notion of 'directness' is critical here (and explored in depth in several of the chapters in User Centred System Design [ND86]). In command line interfaces, the interaction was *mediated*: digital resources (files, words, numbers, shapes) were effectively seen as under the control of the computer and users asked the computer to perform actions on them. In GUIs, users directly acted on the objects themselves, what Draper described as a display (effectively 'digital') *medium* [Dr86]. Effectively user interfaces had moved from communication with a digital agent, to action on a virtual representation of a physical world (down to the trash bin).

Much of the earliest computation was about automation, indeed the Commodore PET, the first true personal computer, was still to be seen in factories and controlling equipment long after it had been retired from the desktop. However, as noted when discussing the role of ergonomics, the shrinking and commodifying of the personal computer meant that for many years HCI focused largely on digital interactions (even if emulating physical ones).

This arc in HCI to virtual physical interaction has changed in more recent years in two ways.

First, has been the increasing focus on *physical interaction* in research on tangible interfaces [IH97] and everyday personal devices and household appliances [DG17].

Second has been increasing *agency* in user interfaces, from recommender systems to virtual agents such as Apple Siri.

These two trends to some extent meet (see table 1), in emerging technology of autonomous vehicles, both domestic (the controversial Google car) and military (even more controversial autonomous weaponry) [HM15]. Slightly less controversially, they also come together in the areas of human–robot interaction and social robotics [BM10].

Table 1. Autonomy and physicality – different combinations

	passive	autonomous
physical	early cybernetics personal devices digital appliances	Google cars autonomous weaponry social robotics
virtual	GUIs and direct manipulation	conversational agents recommender systems

New Paradigms

We have seen some of the trends and threads that characterise changes in the discipline and this has naturally surfaced a number of key challenges and areas that are either currently significant or need to be so. Not least is the way in which computation has ceased to be an optional part of particular aspects of life for certain people, but is becoming an unavoidable aspect underlying all aspects of life for everybody. HCI is becoming as important and all pervading, and perhaps as difficult, as nutrition.

In this last section we will pick up a few more specific changes and challenges.

Health, education and well-being

To some extent these are just 'application' areas, and there are many ways in which either standard techniques can be applied or that these areas spark specific work that is consonant with existing paradigms. For example, Thimbleby's work on seven segment displays [Th13] is highly novel and significant, but still operating within 'classic' interface paradigms.

However, in both health and education we are starting to see systems growing together allowing big data techniques to be applied to determine trends and then feed these back to give individual advice. For example, learning analytics have been used in higher education to predict likelihood that students will fail and then offer appropriate advice [AP12].

This raises specific interface issues, for example, I have considered how best to notify academics and enable them to act on such data [DL15], but it also requires much more 'big picture' whole-systems thinking as all your education data, or all your medical data is being gathered, often imperceptibly, and integrated by different systems, some governmental, some commercial. For example, when I walked around Wales I ended up with 60 days worth of ECG, EDA and other health related data, currently available as open data [DE15]. This is unusual in terms of its pervasive nature, but was limited to a short period. Fitness devices and apps mean that many are beginning to share intimate and personal data without clear understanding of the implications.

So, as well as classic interface design, we have issues of ownership, privacy, visibility and control, some of which will emerge in further topics. In some ways this is not an entirely novel problem, back in 1990 I wrote myself about some of the hidden privacy issues in apparently inconsequential data gathering such as traffic data [Dx90]. However, the widespread nature of such systems now means HCI needs to focus wider than it has been accustomed to over recent years, indeed some are talking about a new area of human–data interaction [HM13].

Socially pervasive applications

Related to the previous topic, many of the trends ended up with strong social challenges for HCI. This is particularly significant if the applications are in some way an essential or socially expected part of 'normal' life. Some such applications are classic screen-based information systems including many aspects of eGovernment, and applications such as Uber and airBnB. While government applications may be mandated (taxes one of the classic two unavoidable things of life), others may effectively become so as initially 'disruptive' applications may effectively become monopolies due to network effects [LM98].

Whereas in health and education, the user issues stretch out from the direct interface into continual and intimate monitoring of life, many of these socially pervasive applications are focused on very specific kinds of activity: paying taxes, hailing a taxi, booking accommodation. Here the stretching is about the way these systems include everyone: that is while health systems may impact large areas of specific peoples lives, these are systems that target a specific area for a large proportion of people.

This is not to say that the direct interface is not significant: Uber's simplicity has been a key aspect of its growth. It is more that this individual interaction spills into social and political changes that are larger than each individual transaction.

Amazon achieved a near monopoly position in online sales of books partly because it spotted early a niche and so established brand, and partly through effective interaction and experience design, such as one-click shopping. However, with this position it has obtained a bargaining power with publishers allowing Amazon to exact levels of royalty that no ordinary book seller can achieve, allowing it to further reduce prices, undercut competitors, and cement its market position. So far, this has been largely to the good of individual consumers, although not necessarily for the industry and the taxman – that is like 20th century factory chimneys the costs are hidden.

Much of the controversy around Uber has been the apparent deliberate attempts to accelerate this process in its area, using massive investment to undercut alternatives, but then exploit this posiion [Ro15,Ta15], as was seen in the Sydney hostage crisis [Ba14].

In general, it seems hard to obtain the benefits of large-scale networks without massive centralisation, but there are exceptions. Freecycle, which helps people give things away, has a small central web site but then locally managed email lists [FC16]. Other crowdsourced sites such as Wikipedia and OpenStreet Map have centralised infrastructure, but decentralised control. All of these are non-profit, but there are companies such as Telerivit, which seem to build effective business models with concern for communities and development [Br14].

We clearly need better understandings of how individual, group and organisational interaction issues interact with social, economic and political structures. This may well stretch the already inter-disciplinary nature of HCI and involve working more closely with those in web and internet science [TH15].

Personal Information – Cloud–based and multi-device

While the 1980s were the decade of the personal computer, the 2010s seem to have finally left that behind, with smartphone access instead of desktop computers and cloud services instead of desktop applications.

There are specific challenges of each development.

Cloud based service raise issues of privacy, ownership, and long-term sustainability. As an example of the latter, Haliyana Khalid studied users of a web based photo-blogging service, starting just before and during the rise of Flickr [KD10]. One of the benefits her users cited for the sue of the web based service was to create a permanent record, and yet by the end of the period most had left it to use Flickr, threatening the economic base and hence longevity of the service that still hosted their older photos.

Multiple device interactions have their own design challenges, not least because they may involve devices owned by different people, often in public places [TQ09,DS10]. Furthermore, the heavy use of 'second screen' and mobile devices for numerous uses from control of home entertainment and heating to accessing public information is likely to create issues with an aging population as deteriorating visual accommodation makes it hard to switch between close and distant screens – for example, needing to switch glasses when looking between remote control and television screen.

However, there is also a more substantial paradigm shift needed. I have previously argued that while the desktop computer has all but disappeared, the models of personal computing are still rooted in this physical heritage [Dx11b].

To some extent this change is already happening with individual cloud applications: you access Facebook whether it is on a phone, TV screen, public access computer, or perhaps soon your glasses. However, when it comes to personal information, such as photos or documents, or even person-to-person messages, we do not have ways to deal with, or even adequately conceptualise that these are all your photos whether they are on Flicker, Facebook or personal cloud storage. Even Dropbox creates a view of a virtual disk.

The personal information management literature has developed language to talk about the life cycle of personal 'stuff' independent of storage and media [Jo07], and there has been extensive work on 'fragmentation', particularly for integrating different kinds of information (files, emails, bookmarks) [BS04, KJ06]. However, we need new ways of pushing this into the interface, metaphors for visualising and interacting with 'my stuff' wherever it is stored and whoever manages that storage, and furthermore having confidence to access it, or at least understand its accessibility, in areas of different network coverage or when devices or companies fail.

Truly invisible

When Weiser introduced ubiquitous computing, he said, "*The most profound technologies are those that disappear* " [We91]; indeed, when the European Commission had a research strand on ubiquitous computing and when Norman write about the issue, they both used the phrase "invisible computer" [No98].

However, Weiser's article is all about displays, small ones (inch scale), medium ones (foot scale) and large ones (yard scale). The 'disappearing' was not about the technology becoming physically invisible, but becoming unnoticed, like a carpet or wallpaper, there but simply part of the background.

However, we are now finding many interfaces literally invisible. Voice interfaces such as Siri or Cortona allow interaction without seeing a screen, and there is substantial work on 'natural user interfaces' often using Kinnect or other non-contact sensors to enable device-less interactions via gestures. It is even possible to use ultrasound to create the feel of objects in mid-air, contactless tactile interactions [CS13].

Most of these are about intentional interactions with computers, which are hidden, but present in mind. However, as noted when we discussed health and education, there are growing numbers of ways in which we are sensed without being aware of it. Schmidt used the term 'implicit interaction' to talk about the semi-intentional ways in which we might naturally tip a device to turn a page [Sc00], but more extreme are 'incidental interactions' [Dx02] where the action being sensed and the effect of it may be quite distinct. The metaphors and mental models for dealing with these are very different from the intentional goal-act-evaluate models, such as Norman's seven stage model [No86,No88], with which we are familiar in HCI. At worst we may end up with a spooky 'ghost in the wall' feeling as things change around us with little understanding of why and the relationship between our activities and their effects.

Even more problematic, as the size of devices reduces and the number of devices proliferate, it is not so much that we are interacting with a single invisible computer, but a more amorphous computational substance permeating the environment. To date, the situation is less extreme than this, but the time is not far off. We urgently need new ways to conceptualise and design for these vast device ensembles, to understand and control emergent behaviours and make sense of the unseen.

Locus of control

One of the problems with invisible computation is potential loss of control. Many of the key user interface design principles are about ensuring that the user is in control: visibility of system state, knowing what it is possible to do, having effective and timely feedback of actions (see fig 4 and 5). This importance of control was also evident in the early hypertext communities concern that users may get "*lost in hyperspace*" [Co87].

> Visibility of system status.
> User control and freedom.
> Help users recognize, diagnose, and recover from errors.

Figure 4. Selection from Nielsen's heuristic evaluation rules [Ni94]

> Offer informative feedback..
> Permit easy reversal of actions.
> Support internal locus of control.

Figure 5. Selection from Shneiderman's Eight Golden Rules [SP10]

However, it is not clear whether this concern is still universally valid. The term "lost in hyperspace" is rarely heard now-a-days, not because users have a greater sense of where they are in complex web-based interfaces, but, apparently, because they do not care, at least for web-based information – if you want to find the information again, there is always Google. In contrast, for desktop PIM only a small percentage of users rely on desktop search, the majority preferring to navigate file hierarchies, despite many users' difficulties managing them.

In the physical world ubiquitous use of GPS, means that people find their way to a destination. In London the famous 'knowledge', where taxi drivers learnt ever street and route is being dropped, but with it apparently the ability to use local knowledge to follow lesser-used shortcuts. Often this does not matter so long as you get to your destination, but this has problems when the technology fails sending you down routes that are evidently foolish (hence the proliferation of 'do not follow sat nav' road signs). Mountain rescue service increasingly have problems with walkers who are using phone based maps and then find themselves without mobile signal, run out of battery or damage the phone. Of course a walker could lose a paper map, but the act of route finding meant that they had a better knowledge of where they were.

Back to the digital world, there is an increasing focus on notification-based systems, helpfully telling you when you have an email message, or someone has liked your recent Facebook post. However, notifications need to come at an appropriate time if they are neither to interrupt nor be ignored [DL15].

Whereas the shift to direct manipulation in the 1980s was all about users controlling the interface, it is almost as if the user is being manipulated or coerced, acting at the whim of the machine. The ramifications of this potentially spread beyond the interface itself – if our systems constantly train people what to do and when to do it, is this ultimately good for an informed citizenry and democracy?

Looking back at the design of the interface itself. There is clearly a mismatch between our user interface design principles and the reality in many systems today. This could be because the systems are badly designed, or it could be because the principles are out-dated, prepared in the days of productivity software not social media. Probably the truth is somewhere between.

Digital fabrication

Even five years ago, laser cutters and digital printers were high-end industrial machines. By Christmas of 2015, low-end 3D printers were in newspaper magazine's 'what to buy your spouse' lists.

For the professional designer this offers the potential for rapid prototyping of the physical form alongside the interactions of hybrid digital–physical goods; experiments have shown subtle effects on interaction depending on the level of physical fidelity of prototypes [GL08]. HCI researchers have also begun to explore novel interactions involving digital fabrication including forms of direct manipulation during the creation of objects [MK13, WA15].

In addition, as with other technological changes, the effects on society may be more profound. We have seen a new DIY movement in 3D printing including a sharing culture of plans. Also major manufacturers are beginning to exploit the just-in-time nature of digital fabrication to reduce the need to hold stocks of spare parts, rather as flexible just-in-time printing has been used extensively in publishing. Both of these offer new challenges for HCI.

More radically would be the point between, if digital fabrication enabled the development of a new kind of digital artisanship, where local makers and menders could repair, customise and modify consumer goods. Even IKEA have announced that people have reached "*peak home furnishings*" and that it is time to recycle, repair and repurpose [We16]. Digital fabrication could offer the potential to answer the consumer society's demand for 'new now' whilst maintaining a carbon footprint consonant with there being a tomorrow.

Mass customisation near the point of use would open complex business, legal, and health and safety issues; for example, who is responsible if a customised microwave catches fire? From an interaction design perspective, we would need ways to ensure that highly customised control panels are still usable, whether through automatic tools to assess end-user designs, or maybe the HCI equivalent of popular fashion or house redecoration television programmes.

Design for solitude

Computers have moved out of the machine room, onto the desktop and now into the pocket. After 30 years of asking for faster processors, wider screens, more pixels, better network connections, larger memory and smaller footprint, increasingly one sees newspaper articles announcing that people feel too available, overloaded with information. Mayer-Schönberger argues that we need to re-learn how to forget in a digital age [MS09], and I have argued that ready availability of information for young children could be harming the very meta-cognitive skills needed to use it [Dx11].

Phoebe Sengers found that spending time on an island community enabled her to re-evaluate the nature and, critically, the pace of IT [Se11], and one of the aims of the Tiree Tech Wave workshop series I organise is to help researchers and makers reflect on their work in a physically and intellectually open environment [DD11]. However, it is not always possible or desirable to travel to an island in order to escape constant digital intrusions.

In an age of hard-to-ignore notifications and copious data at our fingertips, it is time to ask not simply for more computation, but more appropriate computation.

Basic HCI

Finally, after looking at the emerging trends and paradigms, it is wise to look back to our beginnings.

Apple products are often seen as being a touchstone of good usability design. However, if you turn on an iPhone the unlock slider appears up to a minute before it is possible to actually swipe it. Similarly, when you open a MacOS laptop, the password entry box appears long before you can type. In iTunes there are scrolling panes within a scrolling window, where the inner scrolling panes are larger than the outer window so that you need to scroll the outer window to navigate the scrollbar of the inner window. Recently I had a several hundred files selected in the downloads folder ready to move them to an archive, but accidentally double clicked causing them to simultaneously open, and lock up the computer. All of these are basic usability errors, which would be picked up by standard usability principles or the user testing. What is going wrong?

For Apple this is not a recent problem and for some years the focus on surface aesthetics has overridden core usability. Even Don Norman and Bruce Tognazzini have written bemoaning the demise of Apple usability [NT15].

While Apple is an obvious high-profile target when considering poor usability, it is not hard to find far worse examples in other major products.

Clearly there are examples of good usability practice, for example, the team developing the touch keyboard for Windows 8 documented a rich process of experiments and user observations [Si12]. However, it seems that as a discipline we do need to constantly reiterate the lessons of the past as well as look towards the new things of the future.

References

[AS94] Ahlberg, C., Shneiderman, B.: Visual information seeking: tight coupling of dynamic query filters with starfield displays. Proceedings of the SIGCHI conference on Human factors in computing systems: celebrating interdependence. pp. 313–317. ACM, New York, NY, USA (1994).

[AM08] von Ahn, L., Maurer, B., McMillen, C., Abraham, D. and M. Blum, M. (2008). reCAPTCHA: Human-Based Character Recognition via Web Security Measures. Science, 321(5895):1465–1468

[AI77] Christopher Alexander; Sara Ishikawa; Murray Silverstein (1977). *A Pattern Language : towns, buildings, construction*. Oxford University Press. https://archive.org/details/APatternLanguage

[Al79] Christopher Alexander (1979). *The Timeless Way of Building*. Oxford University Press. https://archive.org/details/TheTimelessWayOfBuilding

[AP12] Arnold, K. and Pistilli, M. 2012. Course signals at Purdue: using learning analytics to increase student success. In Proc. of the 2nd International Conference on Learning Analytics and Knowledge (LAK '12). ACM, NY, USA, 267-270. doi:10.1145/2330601.2330666

[Ar09] W. Brian Arthur (2009). The Nature of Technology. Penguin

[Ba14] Naina Bajekal (2014). Uber Charged 4 Times Its Usual Rate During Sydney Hostage Siege. *Time*, Dec. 15, 2014

[Ba85] P. Barnard. Interacting cognitive subsystems: a psycholinguistic approach to short-term memory. In A. Ellis, editor, Progress in the Psychology of Language, volume 2, chapter 6. Lawrence Erlbaum Associates, Hove, 1985.

[Ba88] George Basalla (1988) The Evolution of Technology. Cambridge University Press

[BM10] David Benyon and Oli Mival. 2010. From human-computer interactions to human-companion relationships. In Proceedings of the First International Conference on Intelligent Interactive Technologies and Multimedia (IITM '10), M. D. Tiwari, R. C. Tripathi, and Anupam Agrawal (Eds.). ACM, New York, NY, USA, 1-9. DOI=http://dx.doi.org/10.1145/1963564.1963565

[BJ11] Nathalie Le Bigot and Wolfgang Jaschinski. 2011. Hand position at computer screens: effect on visual processing. In *Proceedings of the 29th Annual European Conference on Cognitive Ergonomics (ECCE '11).* ACM, New York, NY, USA, 85-88. doi: 10.1145/2074712.2074730

[BS04] Richard Boardman and M. Angela Sasse. 2004. "Stuff goes into the computer and doesn't come out": a cross-tool study of personal information management. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04). ACM, New York, NY, USA, 583-590. DOI: 10.1145/985692.985766

[Ba01] Jan Borchers (2001). *A Pattern Approach to Interaction Design*. Wiley.

[Bo14] Zachary Davies Boren (2014). There are officially more mobile devices than people in the world. *The Independent*, Tuesday 7 October 2014. http://www.independent.co.uk/life-style/gadgets-and-tech/news/there-are-officially-more-mobile-devices-than-people-in-the-world-9780518.html

[Br14] Kristen V. Brown (2014). S.F. startup Telerivet's SMS could help developing nations. *SFGate, San Francisco Chronicle*, July 15, 2014. http://www.sfgate.com/technology/article/S-F-startup-Telerivet-s-SMS-could-help-5622382.php

[Bu45] V. Bush. As we may think. Atlantic Monthly, 176(1):101–8, 1945

[Ca91] William Calvin (1991). *The Ascent of Mind: Ice Age Climates and the Evolution of Intelligence*. Bantam Books.

[CM86] Card, S. K. ; Moran, T. P. ; Newell, A. The model human processor: an engineering model for human performance. Handbook of Perception and Human Performance. NY: Wiley; 1986; 2: 45-1-35.

[CS13] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, Sriram Subramanian, Ultrahaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces. UIST'13. October 2013.

[CF09] Chandler, A., Finney, J., Lewis, C. and Dix, A (2009). Toward emergent technology for blended public displays. Ubicomp '09: Proceedings of the 11th international conference on Ubiquitous computing. New York, NY, USA: ACM, p. 101-104 4 p.

[CS99] P. Checkland and J. Scholes, Soft Systems Methodology in Action. John Wiley and Sons Ltd., Chichester, UK, 1999

[Co87] J. Conklin, Hypertext: A survey and introduction, IEEE Computer, 20 (9) :17-41, 1987

[Co87] J. Coutaz. Pac, an object oriented model for dialog design. In H. J. Bullinger and B. Shackel, editors, Human–Computer Interaction – INTERACT'87, pages 431–6. North-Holland, Amsterdam, 1987.

[Cz90]M. Csikszentmihályi, Flow: The Psychology of Optimal Experience. Harper & Row, 1990

[Cy91] A. Cypher. Eager: Programming repetitive tasks by example. In Reaching through Technology – CHI'91 Conference Proceedings, pages 33–9. ACM Press, New York, 1991.

[DF06] Dearden, Andy and Finlay, J. (2006). Pattern languages in HCI: a critical review. Human computer interaction, 21 (1), 49-102.

[DS04] Diaper, D., & Stanton, N. (Eds.) (2004). The Handbook of Task Analysis for Human-Computer Interaction. Lawrence Erlbaum Associates.

[Dx90] A. J. Dix (1990). Information processing, context and privacy. Human-Computer Interaction - INTERACT'90, Ed. D. G. D. Diaper G. Cockton & B. Shakel. North-Holland. 15-20.

[Di91] A. J. Dix (1991). Formal methods for interactive systems. London: Academic Press. http://www.hiraeth.com/books/formal/

[Dx92] A. Dix (1992). Human issues in the use of pattern recognition techniques. In Neural Networks and Pattern Recognition in Human Computer Interaction Eds. R. Beale and J. Finlay. Ellis Horwood. 429-451. http://alandix.com/academic/papers/neuro92/neuro92.html

[Dx95] A. J. Dix (1995). Cooperation without (reliable) Communication: Interfaces for Mobile Applications. Distributed Systems Engineering, 2(3): pp. 171-181.

[DM97] A. Dix, R. Mancini and S. Levialdi (1997). Communication, action and history. Proceedings of CHI'97. Atlanta, USA, ACM Press. http://alandix.com/academic/papers/chi97/ajd.htm

[DM97b] A. Dix, R. Mancini and S. Levialdi (1997). The cube - extending systems for undo. Proceedings of DSVIS'97, Granada, Spain, Eurographics. pp 473-495. http://alandix.com/academic/papers/dsvis97/

[DR00] A. Dix, R. Beale and A. Wood (2000). Architectures to make Simple Visualisations using Simple Systems. Proceedings of Advanced Visual Interfaces - AVI2000, ACM Press, pp. 51-60.

[Dx02] A. Dix (2002). Beyond Intention - pushing boundaries with incidental interaction. *Proceedings of Building Bridges: Interdisciplinary Context-Sensitive Computing*, Glasgow University, 9 Sept 2002. http://alandix.com/academic/papers/beyond-intention-2002/

[Di03] Dix, A. (2003). *A Cybernetic Understanding of Fitts' Law*. HCI Book online!. http://www.hcibook.com/e3/online/fitts-cybernetic/

[Dx10] A. Dix. Human-Computer Interaction: a stable discipline, a nascent science, and the growth of the long tail. *Interacting with Computers*, 22(1), 2010, 13-27. http://alandix.com/academic/papers/IwC-LongFsch-HCI-2010/

[DS10] A. Dix and C. Sas (2010) Mobile Personal Devices meet Situated Public Displays: Synergies and Opportunities. *International Journal of Ubiquitous Computing (IJUC)*, 1(1), pp. 11-28. http://www.hcibook.com/alan/papers/MPD-SPD-2010/

[DS10b] A. Dix, S. Subramanian (2010). IT for Sustainable Growth. *Journal of Technology Management for Growing Economies*. 1(1), pp. 35-54. http://alandix.com/academic/papers/IT-Sustainable-Growth-2010/

[Dx11] Alan Dix. 2011. A shifting boundary: the dynamics of internal cognition and the web as external representation. In *Proceedings of the 3rd International Web Science Conference (WebSci '11).* ACM, New York, NY, USA, , Article 9 , 8 pages. DOI: 10.1145/2527031.2527056 http://alandix.com/academic/papers/websci2011-int-ext-cog/

[Dx11b] A. Dix (2011). The Personal Information Environment beyond the Personal Computer. Keynote i-USEr 2010, Shah Alam and Subang Jaya, 30th November 2011. http://alandix.com/academic/talks/iUser-2011-keynote-personal-inf-env/

[DP11] Alan Dix, Margit Pohl and Geoffrey Ellis (2011). Chapter 7: Perception and Cognitive Aspects. In *Mastering the Information Age Solving Problems with Visual Analytics*, Daniel Keim, Jörn Kohlhammer, Geoffrey Ellis and Florian Mansmann (eds). Eurographics Association, pp. 109–130. http://www.vismaster.eu/book/

[Dx13] A. Dix (2013). The Walk: exploring the technical and social margins. Keynote APCHI 2013 / India HCI 2013, Bangalore India, 27th September 2013. http://alandix.com/academic/talks/APCHI-2013/

[Di14] Dix, A. (2014). Open Data Islands and Communities. available at: http://tireetechwave.org/projects/open-data-islands-and-communities/

[Di15] A. Dix (2015). Citations and Sub-Area Bias in the UK Research Assessment Process. In Workshop on Quantifying and Analysing Scholarly Communication on the Web (ASCW'15) at WebSci 2015 on June 30th in Oxford. http://ascw.know-center.tugraz.at/2015/05/26/dix-citations-and-sub-areas-bias-in-the-uk-research-assessment-process/

[DL15] A. Dix and J. Leavesley (2015). Learning Analytics for the Academic: An Action Perspective. In Journal of Universal Computer Science (JUCS), 21(1):48-65.

[DE15] Dix, A., & Ellis, G. (2015). The Alan walks Wales dataset: Quantified Self and Open Data. In J. Atenas & L. Havemann (Eds.), Open Data As Open Educational Resources: Case Studies of Emerging Practice. London: Open Knowledge, Open Education Working Group. doi: 10.6084/m9.figshare.1590031

[DG17] Dix, A. and Gill, S. (with Ramduny, R. and Hare, J.) (2017). TouchIT Oxford University Press (forthcoming).

[DD11] Jakub Dostal and Alan Dix (2011). Tiree Tech Wave. Interfaces, Summer 2011, p.16-17. http://tireetechwave.org/events/ttw-1/interfaces-article/

[Dr86] S. Draper (1986) Display managers as the basis for user-machine communication. Chapter 16 in User Centered System Design; New Perspectives on Human-Computer Interaction, Donald A. Norman and Stephen W. Draper (eds). L. Erlbaum Assoc. Inc., Hillsdale, NJ, USA. pp. 339–352

[DD12] Dray, Susan, Andy Dearden, V Evers, Melissa Densmore, D Ramachandran, Matt Kam, Gary Marsden, N Sambasivan, Tom Smyth, D van Gruenen and N Winters (2012) Human Computer Interaction for Development: Changing HCI to Change the World, in Jacko, J (ed). *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies, and Emerging Applications*, Third Edition, Chapter 61, pp.1369–1394. CRC Press.

[Dr10] Drewes, Heiko (2010): Eye Gaze Tracking for Human Computer Interaction. Dissertation, LMU München: Fakultät für Mathematik, Informatik und Statistik. https://edoc.ub.uni-muenchen.de/11591/

[EE68] D. Engelbart, and W. English, A research center for augmenting human intellect. AFIPS Conference Proceedings of the 1968 Fall Joint Computer Conference, San Francisco, CA, December 1968, Vol. 33, 395–410. (available at http://history-computer.com/Library/AHI.pdf)

[Es13] Estyn (2013) *The Impact of ICT on Pupils' Learning in Primary Schools* – July 2013. Cardiff: Estyn, Her Majesty's Chief Inspector of Education and Training in Wales. http://www.estyn.gov.wales/thematic-reports/impact-ict-pupils-learning-primary-schools-july-2013

[Fi54] P.Fitts, The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47(6), 1954, 381–391.

[FA13] Michael Fourman, Alan Alexander, et al. (2013) Spreading the Benefits of Digital Participation: An Interim Report for Consultation. Edinburgh: Royal Society of Edinburgh, pp. 22–24.

[FC16] Freecycle Network (accessed 19/1/2016) https://www.freecycle.org/

[FL90] D. Frohlich and P. Luff, Applying the technology of conversation to the technology for conversation. Computers and Conversation. Academic Press, 1990

[GL08] S. Gill, G. Loudon, A. Woolley, J. Hare, D. Walker, A. Dix and D. Ramduny ‐ Ellis (2008) Rapid Development of Tangible Interactive Appliances: Achieving the Fidelity/Time Balance. In Special Issue on Tangible and Embedded Interaction, *International Journal of Arts and Technology*, Vol. 1, No.3/4, 2008, pp. 309 ‐ 331, DOI: 10.1504/IJART.2008.022365

[GC12] Jonathan Gray, Lucy Chambers, Liliana Bounegru (2012). *The Data Journalism Handbook: How Journalists Can Use Data to Improve the News.* O'Reilly Media. available online at http://datajournalismhandbook.org

[Gr06] Adam Greenfield (2006). Everyware: The Dawning Age of Ubiquitous Computing. New Riders.

[GI04] Greenhalgh, C.M., Izadi, S., Mathrick, J., Humble, J. and Taylor, I. (2004). ECT - A Toolkit to Support Rapid Construction on Ubicomp Environments In: System Support for Ubiquitous Computing Workshop - UbiSys04.

[Gr03] Judith Gregory (2003). Scandinavian Approaches to Participatory Design. International Journal Of Engineering Education. 19(1):62–74.

[Gu16] The Guardian (2016). *datablog*. Accessed 18/1/2016 http://www.theguardian.com/data

[HM13] H. Haddadi, R. Mortier, D. McAuley, J. Crowcroft (2013). *Human-Data Interaction*. UCAM-CL-TR-837, University of Cambridge, Computer Laboratory. June 2013. http://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-837.pdf

[HN09] Halevy, A., Norvig, P. and Pereira, F. (2009). The Unreasonable Effectiveness of Data, Intelligent Systems, IEEE , vol.24, no.2, pp.8,12, March-April 2009. doi: 10.1109/MIS.2009.36

[HM15] Hawking, S., Musk, E., Wozniak, S., et al. (2015). Autonomous Weapons: an Open Letter from AI & Robotics Researchers. Future of Life Institute. http://futureoflife.org/AI/open_letter_autonomous_weapons

[HB10] Hendler, J., & Berners-Lee, T. (2010). From the Semantic Web to social machines: A research challenge for AI on the World Wide Web. Artificial Intelligence, 174(2), 156–161. doi:10.1016/j.artint.2009.11.010

[HM12] Hooper, C.J., Marie, N., Kalampokis, E. 2012. Dissecting the Butterfly: representation of disciplines publishing at the Web Science conference series. In Proceedings of the 3rd Annual ACM Web Science Conference (WebSci '12). ACM, New York, NY, USA, 137-140.

[HD12] Hooper, C.J., Dix, A. 2012. Web Science and Human-Computer Interaction: When Disciplines Collide. In Proceedings of the 3rd Annual ACM Web Science Conference (WebSci '12). ACM, New York, NY, USA, 128-136.

[HD13] C. Hooper and A. Dix., Web science and human-computer interaction: forming a mutually supportive relationship. Interactions 20(3), 2013, 52–57. DOI:10.1145/2451856.2451868

[Hu16] E. Hunt (2016). Tay, Microsoft's AI chatbot, gets a crash course in racism from Twitter. The Guardian. Thursday 24 March 2016. https://www.theguardian.com/technology/2016/mar/24/tay-microsofts-ai-chatbot-gets-a-crash-course-in-racism-from-twitter

[IE08] IEEE (2008). Special Report: The Singularity. *Spectrum*, IEEE, 45(10). http://spectrum.ieee.org/static/singularity

[IG15] IGF (2015). Policy Options for Connecting the Next Billion. United Nations Department of Economic and Social Affairs, Internet Governance Forum 2015. (accessed 17/1/2016). http://www.intgovforum.org/cms/policy-options-for-connection-the-next-billion

[IH97] Ishii, H. and Ullmer, B. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97). ACM, New York, NY, USA, 234-241. DOI: 10.1145/258549.258715

[IS00] ISO, 2000. ISO 9241-9 International standard: Ergonomic requirements for office work with visual display terminals (VDTs)--Part 9: Requirements for non-keyboard input devices: International Organization for Standardizalion.

[JR89] Jeff Johnson, Teresa L. Roberts, William Verplank, David C. Smith,. Charles H. Irby, Marian Beard, and Kevin Mackey (1989). The Xerox Star: A Retrospective. *IEEE Computer*, 22(9):11–26. doi:10.1109/2.35211

[Jo07] William Jones (2007). *Keeping Found Things Found: The Study and Practice of Personal Information Management*. Morgan Kaufmann

[KJ06] David R. Karger, William Jones (2006). Data unification in personal information management. Communications of the ACM, Vol. 49 No. 1, Pages 77-82 doi:10.1145/1107458.1107496

[KH02] Keim, D.A., Hao, M.C., Dayal, U., Hsu, M.: Pixel Bar Charts: A Visualization Technique for Very Large Multi-Attribute Data Sets. Information Visualization Journal. 1, (2002).

[KK11] Daniel Keim, Jörn Kohlhammer, Geoffrey Ellis and Florian Mansmann (eds). (2011). *Mastering the Information Age Solving Problems with Visual Analytics*, Eurographics Association, ISBN 978-3-905673-77-7. http://www.vismaster.eu/book/

[KD10] Haliyana Khalid and Alan Dix. 2010. The experience of photologging: global mechanisms and local interactions. Personal Ubiquitous Comput. 14, 3 (April 2010), 209-226. Doi: 10.1007/s00779-009-0261-4

[KP88] G. E. Krasner and S. T. Pope. A cookbook for using the model-viewcontroller user interface paradigm in Smalltalk-80. JOOP, 1(3), August, 1988.

[LM98] Stan Liebowitz and Steve Margolis. "Network Externalities (Effects)" entry in The New Palgraves Dictionary of Economics and the Law, MacMillan, 1998. http://wwwpub.utdallas.edu/~liebowit/palgrave/network.html

[LG14] Liu, Y., Goncalves, J., Ferreira, D., Xiao, B., Hosio, S., & Kostakos, V. (2014). CHI 1994-2013: Mapping two decades of intellectual progress through co-word analysis. Proc. Conference on Human Factors in Computing Systems (CHI), Toronto, Canada, 3553-3562.

[LR00] Loke. S.W., Rakotonirainy, A., and Zaslavsky, A. Enabling Awareness in Dynamic Mobile Agent Environments. Proceedings of the 15th Symposium on Applied Computing (SAC 2000), Como, Italy, March 2000, ACM Press.

[LD89] J. Long and J. Dowell, J. Conceptions of the discipline of HCI: craft, applied science, and engineering. In *Proceedings of the Fifth Conference of the British Computer Society, Human–Computer interaction Specialist Group on People and Computers V*, A. Sutcliffe and L. Macaulay, Eds. Cambridge University Press, 1989, pp.9‑32.

[Lo43] Ada Lovelace (1843). Notes on the translation of Menebrea's paper on Babbage's Analytical Engine. Published in *Scientific Memoirs, Selections from The Transactions of Foreign Academies and Learned Societies and from Foreign Journals*, edited by Richard Taylor, F.S.A.,Vol III London: 1843, Article XXIX. Sketch of the Analytical Engine invented by Charles Babbage Esq. By L. F. Menabrea, of Turin, Officer of the Military Engineers. Quotation accessed 18/1/2016 from http://www.cs.yale.edu/homes/tap/Files/ada-lovelace-notes.html

[MS09] Mayer-Schönberger, V. (2009). Delete: The Virtue of Forgetting in the Digital Age. Princeton University Press.

[MD14] A. Morgan, A. Dix, M. Phillips and C. House (2014). Blue sky thinking meets green field usability: can mobile internet software engineering bridge the rural divide? Local Economy, September–November 2014. 29(6–7):750–761. (Published online August 21, 2014). doi: 10.1177/0269094214548399

[Mo10] Jim Motavalli (2010). The Dozens of Computers That Make Modern Cars Go (and Stop). *The New York Times*, Feb. 4, 2010. http://www.nytimes.com/2010/02/05/technology/05electronics.html

[MK13] Mueller, A., Kruck, B. and Baudisch, P. (2013). LaserOrigami: Laser-Cutting 3D Objects. Proceedings of CHI 2013, pp. 2585-2592.

[MK93] Michael J. Muller and Sarah Kuhn. 1993. Participatory design. Commun. ACM 36, 6 (June 1993), 24-28. DOI=http://dx.doi.org/10.1145/153571.255960

[Ni94] J. Nielsen. Heuristic evaluation. In Usability Inspection Methods. John Wiley, New York, 1994.

[ND86] Donald A. Norman and Stephen W. Draper. 1986. User Centered System Design; New Perspectives on Human-Computer Interaction. L. Erlbaum Assoc. Inc., Hillsdale, NJ, USA.

[No86] Donald A. Norman 1986. Cognitive Engineering. Chapter 3 in User Centered System Design; New Perspectives on Human-Computer Interaction, Donald A. Norman and Stephen W. Draper (eds). L. Erlbaum Assoc. Inc., Hillsdale, NJ, USA. pp. 31–61

[No88] D. Norman, *The Design of Everyday Things*. New York: Basic Book, 1988.

[No98] Donald A. Norman (1998). *The Invisible Computer*. MIT Press.

[NT15] Don Norman and Bruce Tognazzini (2105). How Apple Is Giving Design A Bad Name. *Fast Company*, November 10, 2015 (accessed 19/1/2016) http://www.fastcodesign.com/3053406/how-apple-is-giving-design-a-bad-name

[OG33] W. F. Ogburn, and S. C. Gilfillan (1933). The Influence Of Invention And Discovery. Chapter III in Recent Social Trends in the United States: Report of the President's Research Committee on Social Trends. pp.122–166. Full text available at: https://archive.org/details/recentsocialtren01unitrich

[PP97] P. Palanque and F. Paterno (eds.) (1997). Formal Methods in Human-Computer Interaction. London, Springer-Verlag

[PH85] G. Pfaff and P. J. W. ten Hagen, editors, Seeheim Workshop on User Interface Management Systems. Springer-Verlag, Berlin, 1985.

[PV15] Pinder, C., Vermeulen, J., Beale, R., and Hendley, R. Exploring Nonconscious Behaviour Change Interventions on Mobile Devices. MobileHCI'15 Adjunct, ACM Press (2015).

[Po81] J. B. Postel (Ed.), Internet Protocol, IETF RFC 791, Sept. 1981. https://tools.ietf.org/html/rfc791

[RE14] Research Excellence Framework 2014. http://www.ref.ac.uk/

[Ri06] T. Rickards , Obituary: Enid Mumford, Sociologist devoted to making computers work for people. The Guardian, 3 May 2006. http://www.theguardian.com/news/2006/may/03/guardianobituaries.obituaries

[RM91] Robertson, G.G., Mackinlay, J.D., Card, S.K.: Cone Trees: animated 3D visualizations of hierarchical information. Proc. CHI'91. pp. 189–194. ACM Press, New Orleans, USA (1991).

[Ro15] Brishen Rogers (2015). The Social Costs of Uber. Online Symposium Grassroots Innovation & Regulatory Adaptation, *The University of Chicago Law Review Dialogue*, (accssed 19/1/2016)https://lawreview.uchicago.edu/page/dialogue

[RM13] Rogers, Yvonne and Gary Marsden (2013) Does he take Sugar? Moving Beyond the Rhetoric of Compassion. *Interactions* 20(4):48-57.

[Sc00] Schmidt, A. (2000). Implicit human computer interaction through context. Personal Technologies, 4(2–3):191-199. doi: 10.1007/BF01324126

[Se11] Phoebe Sengers. 2011. What I learned on Change Islands: reflections on IT and pace of life. interactions 18, 2 (March 2011), 40-48. DOI:1925820.1925830

[Sh59] B. Shackel, Ergonomics for a Computer. *Design* 120, 1959, 36–39. (available at http://www.idemployee.id.tue.nl/g.w.m.rauterberg/presentations/shackel-1959.PDF)

[Sc83] Shneiderman, B. (1983). Direct Manipulation: A step beyond programming languages, IEEE Computer, 16(8), 57-69.

[Sh92] Shneiderman, B. (1992). Tree visualization with tree-maps: 2-d space-filling approach. ACM Trans. Graph. 11, 1 (January 1992), 92–99. doi: 10.1145/102377.115768

[SP10] Shneiderman, B. and Plaisant, C., Designing the User Interface: Strategies for Effective Human-Computer Interaction: Fifth Edition, Addison-Wesley Publ. Co., Reading, MA (2010)

[Si12] Steven Sinofsky (2102). *Designing the Windows 8 touch keyboard*. MSDN blog, Microsoft, July 17, 2012. (accessed 19/1/2016) https://blogs.msdn.microsoft.com/b8/2012/07/17/designing-the-windows-8-touch-keyboard/

[SK82] David Canfield Smith, Charles Irby, Ralph Kimball, Bill Verplank and Eric Harslem (1982). Designing the Star User Interface. *BYTE*, April 1982, pp. 242–282

[SM04] Soukoreff, R. W., & MacKenzie, I. S. (2004). Towards a standard for pointing device evaluation: Perspectives on 27 years of Fitts' law research in HCI. *International Journal of Human-Computer Studies*, *61*, 751-789.

[Su87] L. Suchman. Plans and Situated Actions: The Problem of Human–Machine Interaction. Cambridge University Press, Cambridge, 1987.

[Su63] I. Sutherland. SketchPad: A man-machine graphical communication system. AFIPS Conference Proceedings 23, 1963, 323–328.

[Ta15] Erica Taschler (2015). A Crumbling Monopoly: The Rise of Uber and the Taxi Industry's Struggle to Survive. *Institute for Consumer Antitrust Studies, News and Views*, June 2015. Accessed 19/1/2016, http://www.luc.edu/law/centers/antitrust/publications/news_views/

[TQ09] Lucia Terrenghi, Aaron Quigley, and Alan Dix. 2009. A taxonomy for and analysis of multi-person-display ecosystems. Personal Ubiquitous Comput. 13, 8 (November 2009), 583-598. DOI=http://dx.doi.org/10.1007/s00779-009-0244-5

[TH15] Thanassis Tiropanis, Wendy Hall, Jon Crowcroft, Noshir Contractor, Leandros Tassiulas (2015). Network Science, Web Science, and Internet Science. *Communications of the ACM*, Vol. 58 No. 8, Pages 76-82 doi:10.1145/2699416

[TH90] H. W. Thimbleby and M. D. Harrison (eds.) (1990). Formal Methods in Human-Computer Interaction. Cambridge University Press

[Th13] H. Thimbleby, "Reasons to Question Seven Segment Displays," Proceedings ACM Conference on Computer-Human Interaction — CHI 2013, Best Paper Award, pp.1431–1440, Paris, France, ACM, DOI: 10.1145/2470654.2466190

[TC05] Thomas, J.J., Cook, K.A. (2005). Illuminating the Path: The Research and Development Agenda for Visual Analytics. IEEE Press

[Th63] Thompson, E. P. (1963), 'The Making of the English Working Class', Victor Gollancz Ltd.

[TM15] Turchi, T., Malizia, A. and Dix, A. (2015). Fostering the Adoption of Pervasive Displays in Public spaces using Tangible End-User Programming. IEEE Symposium on Visual Languages and Human-Centric Computing, At Atlanta, Georgia, US. 18-22 Oct 2015

[Vi93] Vernor Vinge, "The Coming Technological Singularity," Vision-21 Symposium, NASA Lewis Research Center and the Ohio Aerospace Institute, 30 to 31 March 1993.

[Wa15] Ben Walker (2015) Every Day Big Data Statistics – 2.5 Quintillion Bytes Of Data Created Daily. Virtualization and Cloud News http://www.vcloudnews.com/every-day-big-data-statistics-2-5-quintillion-bytes-of-data-created-daily/

[We16] Webster, B. (2016). People don't need any more furniture, says, er, Ikea. *The Times*, 18th Jan. 2016.

[WA15] Weichel, C., Alexander, J., Karnik, A. & Gellersen, H. (2015). Connected tools in digital design. *IEEE Pervasive Computing*. 14, 2, p. 18-21 4 p.

[We91] M. Weiser. The computer of the 21st century. Scientific American, 265(3):66–75, September 1991.

[Wh66] L. White, *Medieval Technology and Social Change*. Oxford University Press, 1966.

[WF86] T. Winograd and F. Flores. Understanding Computers and Cognition: A New Foundation for Design. Addison-Wesley, New York, 1986.

[WD97] Wood, A., Dey, A., Abowd, G.: Cyberdesk: Automated Integration of Desktop and Network Services. In: Proc. of the Conference on Human Factors in Computing Systems (CHI 97), pp. 552–553, ACM Press (1997)

[WP17]. B. Weyers, P. Palanque, J. Bowen and A. Dix (eds). The Handbook on Formal Methods in Human Computer Interaction. Spronger. 2017 (forthcoming).