Towards Materials for Computational Heirlooms: Blockchains and Wristwatches

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ABSTRACT
This paper explores the contrasting notions of "permanance and disposability," "the digital and the physical," and "symbolism and function" in the context of interaction design. Drawing from diverse streams of knowledge, we describe a novel design direction for enduring computational heirlooms based on the marriage of decentralized, trustless software and durable mobile hardware. To justify this concept, we review prior research; attempt to redefine the notion of "material;" propose blockchain-based software as a particular digital material to serve as a substrate for computational heirlooms; and argue for the use of mobile artifacts, informed in terms of their materials and formgiving practices by mechanical wristwatches, as its physical embodiment and functional counterpart. This integration is meant to enable mobile and ubiquitous interactive systems for the storing, experiencing, and exchanging value throughout multiple human lifetimes; showcasing the feats of computational sciences and crafts; and enabling novel user experiences.

ACM Classification Keywords
H.5.m Information Interfaces and Presentation (e.g. HCI): Miscellaneous; K.1 The Computer Industry: Markets; K.4.m Computers and Society: Miscellaneous

Author Keywords
Heirloom computing; permanence; disposability; sustainability; wristwatches; blockchain; materiality; symbolic value; ensoulment; cryptographic key management.

INTRODUCTION
We wish to suggest a design direction for interactive *computational heirlooms*, based on *distributed, trustless, ubiquitous software applications* and *imperishable, physical, mobile devices*. In this paper, we attempt to take the first step towards integrating a diverse set of perspectives—e.g. design, engineering, and economics—towards a foundation which can motivate and inform design and debate.

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DIS '18, June 9–13, 2018, Hong Kong

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ISBN 978-1-4503-5198-0/18/06...$15.00
DOI: https://doi.org/10.1145/3196709.3196778

We define an *heirloom* as a posession that is meant to be cherished, preserved, used, and possibly maintained, throughout the lifetimes of multiple owners, while in some way embedding an "imprint" of its previous owners [48]. As such, an heirloom enables its owners to store and experience both sentimental and material *value*, while also enabling the transfer of such value between owners.

The question of what factors inspire or compel present and future owners to ascribe heirloom status to belongings has been studied and discussed by numerous authors in design theory, the philosophy of technology, and HCI; who have unpacked in various ways the value in heirloom objects, as well as how it is experienced. Yet, the aforementioned literature indicates that themes pertinent to heirloom status are only associated with data or software in exceptional cases—mainly when significant monetary value is of concern. Reasons for this include the rapid obsolescence of electronic devices [8], and a lack of clear affordances for ownership transfer in the case of software artifacts [57]. In terms of Verbeek's notions of *functional*, *symbolic*, and *material* qualities of items that characterize value in their relationships with their owners [96], the implication is that *the embedding of enduring symbolic value in digital materials is problematic.* This challenge also has broader implications that resonate with computing technologies embodying "values" in ways that can meaningfully address "problems that are unlikely to be solved within a single human lifespan" [25].

We address this issue by considering the materials used to create computational artifacts (see [42, 55]), which are "critical in forming aesthetic and functional qualities of an object" and can embody "unique, symbolic meanings" [43]. We first present a distillation of the literature that investigates the question of "what makes an heirloom," through both empirical and philosophical approaches, and particularly as it relates to digital materials (i.e. "software, electronics, and telecommunications" [55]). After unpacking a number of indicators and priors of heirloom status, we move on to consider the case of *the blockchain as a particular digital material* which affords their embedding; and we expand on the possibilities and issues associated with this material. We then consider the example of *mechanical wristwatches* as a genre of *physical, mobile devices*—converse to blockchain-based software as their *digital, ubiquitous* counterpart—that exemplify the embodiment of heirloom properties, pointing out how similar

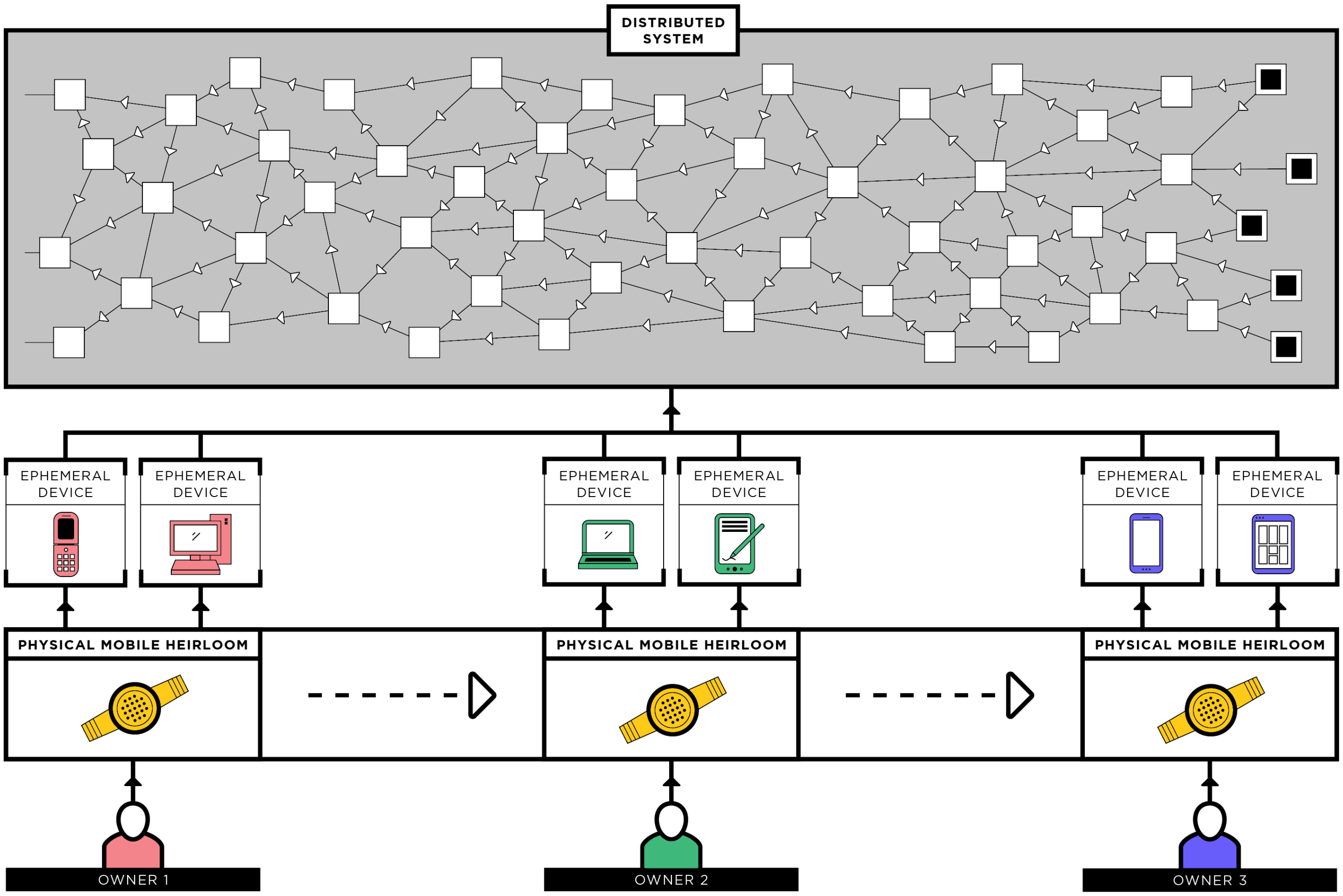

Figure 1. Our vision for mobile and ubiquitous computational heirlooms. The data and/or the computation endures on a blockchain-based distributed system through generations of users, along with a durable, mobile, physical artifact that can be used for authentication and interaction. On such time scales, spanning multiple generations, we consider electronic devices such as computers and smartphones to be "ephemeral." (The diagram for a blockchain-like distributed system is based on the "tangle" concept from [77].)

devices can tackle issues of user authentication and access control that are essential for the usability of blockchain-based software. Apropos, we argue for a design direction for *for computational heirlooms* based on (1) blockchain-based software, (2) mobile artifacts informed in terms of materiality and formgiving practices by mechanical wristwatches, and (3) *ephemeral* interactive devices to connect the two together (see Figure 1).

Our approach draws on secondary research, literature synthesis, and research *for* design (see [24, 25, 51]); aiming to contribute provocations and resources for design and debate around the diametrical notions of *permanance and disposability*, *the digital and the physical*, and *symbolism and function* in the context of interaction design. Through an exploration of these topics, we identify and articulate a specific design direction, which, on a speculative level, deals with the notion of computational heirlooms; and on a more practical note, addresses usability and user experience issues in cryptographically secured systems.

WHAT MAKES AN HEIRLOOM?

The question of what it takes for objects to be cherished and preserved throughout the lifetimes of their owners, and possibly across generations, has been addressed by scholars from multiple perspectives. Insights that are most pertinent for our purposes come from strands of design research literature that deal with the themes of *sustainability* and *inheritance*; where researchers have tackled relevant questions by distilling prior theoretical works and conducting empirical studies to understand the perspectives of owners.

Heirloom Status in Sustainable Interaction Design

The motivation for our concept of computational heirlooms is partly grounded in themes that characterize the scholarly "genre" of *sustainable interaction design* (SID) [15]. The principal position in SID literature is one that intends to persuade designers to take a stand against the convention of rapid obsolescence in the design of consumer electronics; and if necessary, reconsider their materials and challenge the methods and assumptions of HCI in the process [8, 15, 100]. Another subtle but relevant attitude in SID is the foregrounding of technology and the design of artifacts—versus contextual and cultural approaches that highlight policy, education, etc.—as a means to provide solutions[1]. Finally, we note our agreement

[1] See [36] for a similar comparison between music and law.

	Enduring		
Old	Vintage chronograph	[OPPORTUNITY SPACE]	New
	Feature phone with various colorways	Designer laptop	
	Short-lived		

Table 1. The present work relates to the "opportunity space" for *new* and *enduring* designs identified by Pan et al. in their investigation of "fashion consumption factors" [74].

with the SID notion that "packagable methods" in HCI "support a wasteful rapid obsolescence cycle" by failing to take into account long-term effects and changing needs and contexts, and that engaging with "other disciplines with a longer history" is necessary to overcome this limitation [14].

An early articulation of the SID perspective is Blevis' (2007) framework that conceptualizes it in terms of certain "values, methods, and reasoning," suggesting a rubric comprising 10 heuristics to assess instances of SID, and a set of design principles to guide SID practice are suggested [8]. Notable here is the appearance, verbatim, of "achieving heirloom status" as one of the aforementioned heuristics in the rubric; where heirloom status is defined as "long-lived appeal that motivates preservation such that transfer of ownership preserves quality of experience, directly or indirectly." Blevis has also proposed "promoting quality and equality" as a principle for SID, which advocates for "quality as a construct for affect and longevity," as well as "providing equality of experience to new owners [...] whenever ownership transfers."

Building on [8], Pan et al. (2012) have explored the intersection of SID and fashion, postulating that "form, including quality of materials and visual appeal" can be a significant indicator for enduring value [74]. Notably, from their perspective of "fashion thinking," the authors have identified the intersection of the "new" and "enduring" as an underexplored "opportunity space" for design (see Table 1).

In SID literature, the notion of heirloom status is frequently tied to Nelson and Stolterman's (2003) concept of "ensoulment," which relates to the symbolic value embedded in an object through factors such as exquisite craftsmanship in its making and historical or sentimental significance [64]. In a follow-up to [8], Blevis and Stolterman (2007) have taken up ensoulment as "part of an ethical imperative to promote sustainable design" [9]. Among the responses to their survey with more than 450 participants regarding what kinds of artifacts are ensouled and ascribed with heirloom status, "conspicuously absent or seldom mentioned are interactive devices, including computers, video games and video game hardware, cell phones, GPS devices, PDAs and so forth." This is even more interesting considering that certain comparatively inexpensive and disposable items such as clothing, books, and photos are featured frequently among the responses; along with intangible assets such as companies, money, values, and knowledge.

Further building on [8] and [9], Odom et al. (2009) have used the method of "personal inventories" to investigate the question of why some items are preserved by their owners for long, while others are discarded quickly [70] (see also [66, 68]). The theoretical framework for their investigation is based primarily on Verbeek's notions of *functional*, *symbolic*, and *material* qualities of items that characterize value in the relationships with their owners [96]. Based on their data, Odom et al. have proposed a quaternate clustering of factors that explain the attachments between owners and objects: physical *engagement* during use, preserving *histories* of past use or other memories, *augmentation* by the owner beyond the original design, and *perceived durability*. Gegenbauer and Huang (2012), using the same method and working with a different population, have subsequently expanded these categories with the addition of *earned functionality*, *perceived worth*, and *sufficiency* [30]. Finally, Jung et al. (2011) have mined 15 "deep narratives" for "detailed accounts of relationships between each participant and a single particular loved artifact or collection of a single type" [41]. Their analysis reveals three themes that motivate heirloom status—intimacy developed over time, effort expended to understand and control the artifact, and implicit (i.e. symbolic) values—which are summarized in the "unifying notions" of *rarity* and *aficionado-appeal*.

Heirloom Status and Ownership Transfer

In the works discussed above, the foreground is often the behavior and experience of the current user of an heirloom artifact. Another strand of research that informs our concept investigates the practices, experiences, and design considerations around the *transfer* of ownership, and more specifically, the *inheritance* of digital artifacts between family members[2].

A seminal work by Kirk and Banks (2008) notes the "intriguing possibilities for how people might relate to information that will represent or be concerned with them after they are gone," and ponders: "How will those left behind relate to the digital, and can we have the kinds of emotional relationship with digital artefacts or digital memories, if you will, that we might currently have with artefacts of the physical world?" [48]. Following this, Odom et al. (2010) have investigated the HCI issues around death and the inheritance of digital artifacts [69], observing that heirloom status may be ascribed to "*objects of personal significance*" that relate to personal relationships with the departed, and "*objects of historical legacy*" that symbolize family history and legacy.

In later work, Odom et al. (2012) have used 3 prototypes for heirloom artifacts as "technology probes" [33] meant to "provoke discussion about how technology might support (or complicate) their existing practices" around how digital artifacts may be passed down in a family [67]. Three important and interconnected themes that relate to the design of computational heirlooms in our context emerge from this study. First among these is the issue of *persistence*. Among study participants, "a general distrust over the longevity of their personal computers" and other storage devices (e.g. CDs and

[2]Questions and practices around ownership transfer do feed back into the experience of current ownership. For example, Belk (1988), reporting on previous studies spanning multiple generations of individuals [13, 60, 79, 80], notes that "as we age the possessions that people cite as 'special' tend increasingly to be those that symbolize other people," e.g. gifts [6].

external hard disks) is noted. In practice, this translates to a requirement to maintain multiple clones of the data to guard against hardware failures, which is a cumbersome practice. The alternative of using online services (e.g. Facebook, Flickr, Dropbox) has emerged as a facility for sharing, but was not preferred for storing data of sentimental value, due to concerns over the privacy and persistence of data. As such, the authors have noted that "a storage system distributed among [known] people was an appropriate way to preserve familial content." Second is the issue of *aesthetics*. Study participants have revealed that "the aesthetics of physical media failed to convey the preciousness of the content," implying that the forms and materials of conventional computing devices, often designed to function as appliances and tools for work, do not resonate with the sentimental (i.e. symbolic) value of the content. Finally, there is the issue of *embodiment*. The authors have observed that "a primary theme across interviews centered on how capturing digital family archives in forms distinct from the computer might both project and engender a deeper sense of care for these materials." Quotes from the interviews reveal that families often prefer to keep cherished heirloom objects in designated places in the home, and the act of engaging with these artifacts as a distinct physical activity (in contrast to, for example, browsing photos on a computer) contributes to the experience.

Other authors, exploring similar themes, have focused on how computing technologies interact with the experiences of loss, bereavement, and remembering (e.g. [49, 57, 58]); their insights will be discussed at a later point in this paper.

Table 2 itemizes a summary of relevant concepts extracted from the literature discussed above. Here, we note the prevalence of notions such as longevity, rarity, and aesthetics, which relate to the *materiality* of artifacts, i.e. *physical affordances*; while issues around data persistence and privacy relate to the *affordances of the digital* (see [49]). We will argue in the next section that a broad conception of what *material* denotes can serve as a unified scaffolding for design considerations that relate to both physical and digital aspects of computational heirlooms. Based on these ideas, we will subsequently propose blockchain-based software as a design material for computational heirlooms.

MATERIALS AND COMPUTATIONAL HEIRLOOMS

The notion that computational artifacts are made of "digital materials" that are given "forms" by designers and craftspeople is a common theme in interaction design literature [93]. Scholars have investigated this theme building on various backgrounds and with differing granularity. An oft-cited work by Löwgren and Stolterman (2004) describes software as a versatile "material without qualities" [54]. Jung and Stolterman (2011) have discussed broad conceptions of "material" and "form-giving" in the context of digital artifacts, which motivates their vision for "form-driven interaction design" [42, 44]. Dourish and Mazmanian (2011) have unpacked different ways of conceptualizing the materiality of digital artifacts, noting how both the "metaphors" and "representations" of digital information have a material impact on the user experience and the society as a whole [16]. Lindell (2014) has adopted a

Main Theme	**Concepts**	**Source**
Sustainability	Longevity; "achieving heirloom status" as a heuristic for SID; "promoting quality and equality" as a design principle.	[8, 14, 15, 100]
Fashion	Aesthetics (i.e. materials and form) as a symbol of enduring value; the "opportunity space" in the intersection of the "new" and the "enduring."	[74]
Ensoulment	Engagement, histories, augmentation, perceived durability, earned functionality, perceived worth, and sufficiency to characterize attachment in ownership relationships; rarity and aficionado-appeal of objects; intangible assets such as values and knowledge as heirlooms.	[8, 9, 30, 41, 64, 66, 68, 70]
Inheritance	"Objects of personal significance" and "objects of historical legacy"; persistence, aesthetics, and embodiment as important aspects of the heirloom experience.	[48, 69, 67]

Table 2. Summary of concepts relevant to attachment and heirloom status from interaction design literature.

more fine-grained approach, focused on the experiences of programmers who "craft" artifacts using code as a material, and commented on the material properties of different programming languages to motivate a conception of programming as a craft [52]. Vallgårda and Redström (2007) have introduced the notion of "computational composites" to characterize physical materials that are controlled to dynamically change state [94].

Our understanding of digital materials is based on Löwgren's (2007) simple description: "software, electronics, and telecommunications" [55]. Here, the idea that all three of software, electronics, and telecommunications are materials that a designer can choose and manipulate calls for a broad interpretation of *what a material is*.

We consider a material and its qualities to be one and the same. In more poetic wording, we think of *materials as qualities*. We reject the dualistic idea that the physical manifestation of a material is distinct from its qualities or properties; and embrace the possibility to treat software and telecommunications protocols—essentially, *rules* that govern the behavior of electronic substrata—as *materials* proper. We submit that any substratum for human labor[3] is a material; be it steel, wood, leather, recycled bottles, FR-4, C++, a binary tree, or the User Datagram Protocol. More precisely, we use the term 'material' to denote a collection of *constraints and affordances for making* that are associated with a thing. Furthermore, we would like to note that the properties of a material may be dependent on the particular medium in which it exists. Just as structural materials may behave differently in air, water, or space, and have properties that change with environmental conditions;

[3]The wording invokes Marxian economics, where "material" is conceptualized as a "substratum," "furnished by Nature without the help of man" [56]. The converse of material is the "labor" that gives it form. An artifact is made out of materials shaped by "human labour [...] embodied or materialised in it."

the behavior of computational materials is dependent on the substrate for their implementation.

With regard to the aesthetics and symbolic perceptions of electronic devices as heirlooms, a common approach is based on the use of natural, durable, and repairable materials for structural, decorative, and interactive purposes to invoke perceptions of durability and familiarity [70, 67, 92, 91]. Further, as Fernaeus, Jonsson, and Tholander (2012) have noted in their examination of a Jacquard loom from the mid-1800s[4] from the perspective of contemporary HCI [20], it is possible to reveal information and computational abstractions that drive the functionality of a device through "materiality" and "graspability" (see also [35]). In said study, this property is reported to motivate a unique bond between the loom and the craftspeople who operate it. Such a design stands in contrast to current computing devices, which are sealed and unrepairable, and have user interfaces built around screens and generic input methods that sacrifice transparency for mutability. However, while it is possible to mitigate interaction issues through design, in the case of the electronic substrate of digital materials, which often literally underlies their physical surface, a key constraint that needs to be acknowledged in our context is the issue of *longevity*.

An overwhelming majority of contemporary computing artifacts – especially mobile devices – are intentionally designed, manufactured, and marketed assuming a planned obsolescence of only a few years [10]. Many scholars foreground business factors, along with social and personal motives, in explaining this phenomenon [8, 10, 74, 76]. However, planned obsolescence is not purely a folly of business and fashion. Even in the absence of misuse or manufacturing defects, electronic devices will fail eventually due to *wearout*. The physical processes that enable functionality in electronic components continuously damage them over time and inevitably degrade functionality [87]. One such process is electromigration—the erosion of conducting material in circuits by continuous current flows [53]. Another has to do with heat- and radiation-driven distortions in the crystalline microstructures of semiconductor and insulator components [86].

Wearout in electronics is analogous to the effects of strain and fatigue in mechanical devices, but while most macro-scale mechanical devices can be repaired, it is not possible to mend failing integrated circuits. Most modern electronic devices are designed to be completely thrown away in case of failure, as the cost of repair exceeds the cost of replacement. Some devices are designed so that circuit boards or individual components may be replaced, but this is predicated on the availability of said components from a vendor who has the incentive to produce and distribute them. Integrated circuits are often highly complex and proprietary designs, and even if the designs were available, manufacturing them is a prohibitively expensive undertaking that only makes sense if very large quantities are to be produced [11]. Over time, through technological change and market forces, the means

[4]The Jacquard loom is an artifact of importance to the history of computing, by way of pioneering the use of punch cards to automate the reproduction of complex patterns [78].

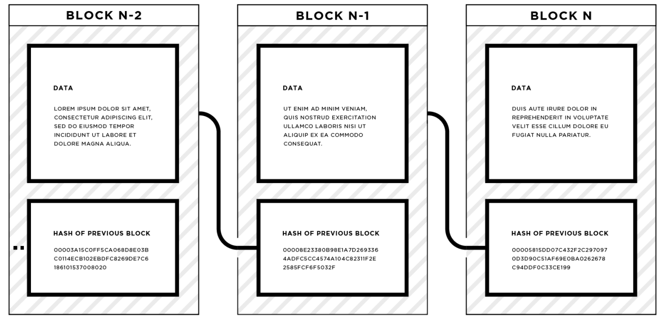

Figure 2. A simple example for a blockchain data structure.

to manufacture the spare parts necessary to maintain many computing devices are lost. These limitations are imposed by the very technologies that enable modern computing artifacts to assume their current forms and functions. It would not be possible to pack modern computing functionality into current mobile form factors if repairability and longevity were primary concerns. *Wearout is an intrinsic property of digital materials that designers must acknowledge*[5].

Conversely, the lifetime of the computational processes and data—rather than the devices on which they live—may be extended by way of multiple backups. These backups can be maintained as local copies by the owner of the data, or be trusted to a cloud service. However, using cloud services to store sensitive information introduces privacy concerns and dissonance in the user experience (see [67]), while failing to offer a decisive solution to the main problem with maintaining backups: that *the persistence of the data or computation is predicated on the survival and incentives of a single entity*. To deal with this problem, we suggest the use of distributed and cryptographically secured systems—in particular, blockchain-based software—as a design material.

THE BLOCKCHAIN AS A DESIGN MATERIAL

The basis for a blockchain is a data structure comprising a list of records (blocks) that are cryptographically connected to each other, in a certain order. This architecture is similar to the linked list, a rudimentary data structure in computer science, with the difference being that each block uses a cryptographic hash of the previous block to refer to it, rather than a pointer (see Figure 2). The use of a cryptographic hash in lieu of a pointer introduces the property of *immutability* – that a record at any point in the blockchain, once it is written, cannot be altered without having to revise the entirety of the data. It is straightforward to *append* a record to the blockchain data, but removing or changing existing records is not.

The principal use case for the blockchain data structure is that of a *trustless distributed data store* where every single node on a network holds a copy of the entire blockchain data. The distributed nature of the system affords high reliability and survivability [4] (see Figure 3. In turn, the blockchain

[5]Apropos, as this paper was being written, the graphics processor on the first author's 3-year-old personal laptop has failed due to wearout and rendered the computer unusable. The chip cannot be repaired or replaced. The recommended fix was to replace the entire mainboard.

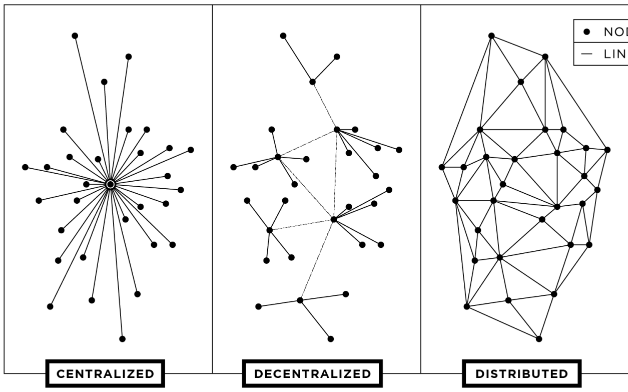

Figure 3. Compared to centralized systems which are vulnerable to the failure of a small number of points, distributed systems can be architected to operate coherently in case of multiple failures within the network. As such, data and computation is more resilient in a distributed system, despite adversities. (Drawing based on a figure from [4].)

data structure enables trustless operation, where the correctness of retrievals and the validity of additions can be verified efficiently (see [17]). As such, a blockchain proper, in addition to the data structure, comprises a specific consensus protocol specifying how data is to be written and retrieved, along with a set of incentives to reward entities who contribute computing power towards maintaining nodes in the distributed system. If a conventional list or database were used in lieu of a blockchain structure, such a system would be either infeasible, or rely on information provided by a trusted authority. Thus, the promise of the blockchain is to enable *robust cooperation among computing entities without placing trust on a central authority* to rule over the effort.

The blockchain was initially meant as a means to enable "a purely peer-to-peer version of electronic cash" which allows for value transfer between parties "without going through a financial institution" [63]—a *cryptocurrency*. The technology has subsequently seen widespread adoption and served as the basis for numerous new applications and developments. These include using blockchain technology as a registry for the ownership of internet domain names [1] or to prevent fraud by documenting the provenance of high-value physical assets [7], storing and executing code on a blockchain [99], and variations on the technology that aim to overcome its technical limitations [77]. From a user-centered perspective, in their report on interviews with a specific focus on blockchain-based payment systems, Baur et al. (2015) note that "interviewees of all groups also mentioned the underlying blockchain as an idea and technology that could have a far-reaching, disruptive potential outside of the payment area. Applications as diverse as document version control, proof of whether a person's vote has been counted or clear identification for e-government and open data solutions were addressed" [5].

In sum, a blockchain is a distributed, immutable, append-only data store. Seen as a digital material, these properties imbue the blockchain with the affordances that are necessary for it to serve as a *substrate for computational heirlooms designed to be useful throughout the lifetimes of multiple owners, while bearing marks of their previous owners*.

Despite these characteristics of blockchain technology (and its potential successors) that would suggest it could enable novel user experiences, and despite the recent surge of attention to cryptocurrencies and related technologies in commercial media and engineering communities, the HCI literature on the topic is nascent. The existing research, in terms of Forlizzi and Batterbee's (2004) unpacking of the user experience of interactive artifacts, represents "product-centered" and "user-centered" approaches, but not "interaction-centered" viewpoints that can foreground the user's "relationship" with a blockchain-based system (see [22]).

In the intersection of design research and blockchain technology, Maxwell et al. (2015) have presented a "tangible system of Lego and colored stickers to allow participant-actors to physically enact transactions on a Blockchain"—i.e. physicalization of the inner workings of the technology—for educational purposes, but they do not comment on the physicalization of end-user interactions [59]. Foth (2017) has proposed a number of HCI and design themes in relation to blockchain technology—including the use of blockchain technology *for* HCI research—but expressive aspects of the user experience are not among them [23]. Jabbar and Bjørn (2017) have conducted an ethnographic study on entrepreneurs working on blockchain infrastructure and products, but their scope does not extend very much to the end-user [37]. Chanson et al. (2017) have implemented a blockchain-based system for preventing automobile odometer fraud, but an investigation of "user interaction with the system" is left for future work [12]. Jaffe et al. (2017) have described a system of financial incentives to promote urban cycling, and presented a proof-of-concept implementation where bicycle-mounted sensors communicate over a cellular network with a blockchain-based database and computing platform [38]. Here, the coupling of a blockchain-based software component to the physical hardware is central to the concept, but again, no empirical studies on the user experience are presented. Finally, Khairuddin et al. (2016) [47], followed by Sas and Khairuddin (2017) [83], have conducted user-centric explorations of design issues around a cryptocurrency through interviews with 20 participants, but they focus on legal, sociological and economic issues such as regulation and trust between parties in transactions. Notably, their account concludes by pointing at the "materiality of bitcoins and the feasibility of technological innovations supporting it," especially "ways for materializing the bitcoins" as an important direction for future research [47].

The research summarized above motivates the potential of the blockchain as a material for novel user experiences and points to peripheral issues. Another strand of research exposes an issue that is central to our argument (for using durable physical artifacts as a means for interacting with the software): that of *identity validation and access control*; which is essential for usability and "good" user experience in blockchain-based systems (and cryptographic applications in general).

Similar to username and password pairs used to manage ownership, access, and authorization in any kind of software, blockchain-based software requires that users generate and maintain a set of public and private keys. While conventional usernames and passwords can be composed of mnemonics, for a variety of engineering and security reasons, private keys used to access cryptographically-secured systems often do not have representations that can be easily read and remembered by humans. Public keys (and related information such as addresses for sending and receiving cryptocurrencies), commonly being mathematically derived from private keys, are also not designed to be processed by humans. Moreover, in most cases, users are required to generate, store, and use numerous cryptographic keys over the course of their interactions with a system, and it is undesirable to send private keys over computer networks. The need to manage multiple instances of highly sensitive data that cannot be read by humans and should not be transferred over networks, needless to say, engenders serious usability issues and a dissonant user experience.

In a seminal study on the usability of cryptocurrencies and related software, Eskandari et al. (2015) have reviewed methods and tools for storing and managing private keys for cryptocurrency wallets, where they identify “key management” as a fundamental usability issue in the Bitcoin ecosystem [18]. Krombholz et al.’s (2016) later large-scale survey and interviews on the habits of cryptocurrency users confirms this finding [50]. In both studies, safety and reliability in the storage and retrieval of private keys and public addresses are revealed as essential usability issues in a cryptocurrency ecosystem. Current end-user strategies for ownership and access management are reported to heavily rely on the use of online services which introduce a trusted third party as a custodian to private information, which negates one of the principal benefits of the technology; and the use of “paper” backups, which introduce additional workloads and lead to user “discomfort” as the materiality of paper does not resonate with the underlying technology. Moreover, about 20% of the respondents to their survey have indicated that they have lost private keys, and thereby valuable assets, mainly through misuse or failures on a digital device where the keys were stored. The literature on end-user interactions with e-mail encryption systems also agrees with the above on the nature and significance of pertinent usability and human factors issues [27, 28, 29, 98, 85]. It is also notable that participants in Kromholz et al.’s study “proposed a dedicated device with an intuitive UI for key management and think that such an artifact would be the most secure and usable option."

The aforementioned studies explore functional aspects and usability issues related to key management. Going back to Forlizzi and Batterbee’s terminology, in these studies, “cognitive” and “fluent” dimensions of interactions are the center of attention, rather than the “expressive” dimension that would relate to the themes of emotion, attachment, materiality, and stories (see [22]). Conversely, we would argue that in the case of sensitive and valuable data and computation—e.g. high-value assets, objects of “personal significance” and/or “historical legacy” (see [69])—“expressive” interactions that “help the user form a relationship to the product” are significant (see [22]). Furthermore, as prior studies of heirloom status, product attachment, and disposal/preservation behaviors show, *affective relationships that owners have with artifacts can induce behavior that promotes careful use and maintenance*,

Figure 4. "Exhibition caseback" on a mechanical wristwatch, displaying *functional*, *symbolic*, and *material* aspects of value. In addition to functioning as a robust chronograph, the piece is “ensouled” through craftsmanship and precious materials, and symbolizes virtue (e.g. bravery, scientific achievements) by way of being the "first watch worn on the moon." (Photo by Wikipedia user MadGeographer, CC BY-SA 3.0)

even in the presence of functional and usability defects [30, 41, 66, 68, 70, 69]. As such, we propose that investigating *mobile, mechanical devices, inspired by materials and formgiving practices already used in heirloom artifacts, can inspire an appropriate angle of attack* for addressing key management issues blockchain-based software and other cryptographic systems.

Furthermore, we submit that utilizing physical hardware for key management will serve to *communicate to users a more truthful mental model of the inner workings of the system*. For example, a commonly held notion that it is possible to *possess* cryptocurrencies or other blockchain-based data. This mental model has roots in the way that we approach cash and other assets, along with how we think about data on a computer or in the cloud—for instance, Kirk and Banks (2008) have written that “in some cases the digital content may never even truly live *in* the object, as for example might be the case with cloud computing where the data *lives* somewhere else only *occurring* in the object as it is needed.” [48]. In reality, with blockchain-based software, the data itself almost never “occurs” inside whatever device one might be using to access it—the data and computation occur as part of a distributed system, of which the local device is often not a part. What the user has in their possession is merely the keys which grant certain privileges over certain parts of that system.

THE CASE OF MECHANICAL WRISTWATCHES

Mechanical wristwatches are a genre of products that show up pertinently and consistently in studies of heirloom status (see [9, 41, 72, 74, 75]) and can embody many (if not all) of the factors that have been elicited in empirical studies of product attachment (see Table 2). Certain properties of these products clearly reflect the basis for this association. First, the *materials* from which mechanical watches are made—precious and/or technically advanced metals, jewels, leather for straps—promote a perception of longevity and afford maintainability. In the context of interaction design, Tsaknaki and Fernaeus (2016) point out that such “organic” materials "seem to have a greater potential for adaptation and repair, and also address a more varied view on culture and ever-changing contexts of use," thereby affording "*liveness*" – the sense that the materials with change over time – and promoting practices "accepting the need for some caretaking over time" [90]. Second, they are not dependent on any electronic components that are susceptible to invisible wearout. Strikingly, this is reflected in that manually wound or self-winding mechanical wristwatches being marketed as cherished heirloom objects, while battery-powered "quartz" watches with electronic circuits are perceived as lesser, disposable items [2, 88]. The absence of electronic components also begets a *resistance to technological change* (see [72]). Albeit costly, components inside a mechanical watch of even over a hundred years of age can be maintained, repaired, and reproduced, and hence the watch can be maintained indefinitely, by a skilled watchmaker. In contrast, repairing or reproducing individual integrated circuits in an electronic device in the same way would be almost completely infeasible. Third, the *design* of wristwatches, through a preference for precious materials, crafsmanship, advanced manufacturing processes, and of course, marketing, has over time engendered a culture which promotes a perception of wristwatches as *ensouled* [2, 88, 62] (see Figure 4). Finally, the purely mechanical functionality and user interface on a wristwatch (including passive interactions such as the mere act of wearing it) beget a strong sense of *physical engagement*.

As such, we propose a *design direction for computational heirlooms*, based on an enduring dyadic system comprising blockchain-based software, and mobile artifacts inspired by wristwatches to be used for the management of cryptographic keys. These two imperishable components of the system would be connected together via electronic devices (personal computers, smartphones, or any future inventions) that can be considered *ephemeral*, owing to the nature of their digital materials. While the electronic devices that run the blockchain-based software and interact with it may change over time, the data and computation, as well as the physical artifacts used to access it, are expected to survive indefinitely[6].

One principal limitation of our proposal is that we do not present any concrete prototypes that illustrate the concept, barring a designer’s sketch for what a wristwatch-inspired cryptographic key management device may look like (Figure 5). The first reason for this is to maintain focus in terms of the scope of this paper, concentrating on providing a logical basis for the concept by synthesizing findings and insights from previous work. Following the design direction that we are proposing calls for the fusion of multiple streams of knowledge, and here our aim is to distill those streams into an entry point for designers of interactive systems. The second reason why we do not present concrete designs is to higlight the fact

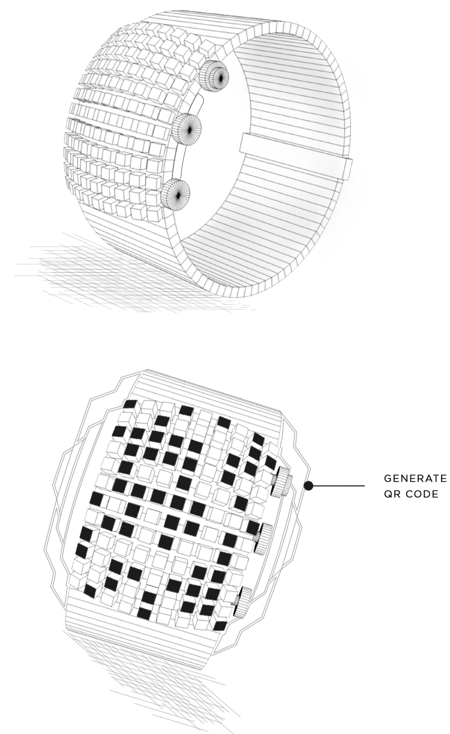

Figure 5. A product designer’s concept sketches for a wristwatch-inspired cryptographic key management device.

that constructing a wrist-mounted mechanical device for managing modern cryptographic keys is actually not within the means of current technology.

The generation and utilization of cryptographic keys involves sophisticated computations. Theoretically, it is indeed possible to construct purely mechanical devices that implement modern cryptographic computations without electronic circuits. However, we are not aware of any kind of technology that would allow such devices to fit in a form factor that would be mobile, let alone wearable on a wrist. Such devices would be more on the scale of buildings. Thus, proposing that mechanical wristwatches can be an inspiration for end-user cryptographic key management systems may seem bizarre to some readers. However, this limitation does not subvert our goal, which is to draw on *research for design* [24, 26, 102] and explore the intersection of interaction design and fiction, providing a *basis and background for design* by exposing visions, requirements, inspirations, and hypotheses to inform subsequent conceptual, technological, and scientific work (see [61]). Moreover, through this seemingly bizarre proposal, we wish to make two additional interconnected points.

The first point we would make is that mechanical wristwatches are in no way an *ideal* manifestation of the notions they ought to embody. As with any artifact, they are not indestructible—in fact, many fine wristwatches are not even waterproof. Their function is not essential—in this day and age, it is hard *not*

[6]This concept is also meant to invoke the notion of the ensoulment of a collection or system of things, rather than single artifacts, as exposed in Blevis and Stolterman’s (2007) survey [9].

to encounter countless time-telling devices through the day. The truth is that the notion of wristwatches as objects to be cherished and passed on through generations has to do with *perception* alone. There is nothing innate in wristwatches that grants them heirloom status; on the contrary, as studies indicate, it is often the owners' symbolic relationships with them that induce behavior which begets longevity [30, 41, 66, 68, 70, 69]. Furthermore, the notion of wristwatches as a special kind of heirloom is a recent one, which has been largely cultivated through marketing efforts of Swiss watchmakers who were decimated by the introduction of cheaper electronic "quartz" watch movements in the 1970s. The "comeback" of the Swiss watch industry in the face of competition in the 1980s, through efforts to alter the public perception of their mechanical craft objects, is given as an example of "non-technological innovation" in business literature [39, 88]. The success of the effort is evident in that a very prominent Swiss watchmaking company, whose watches are renowned for being some of the most expensive in the world (as well as for holding and even increasing their monetary value as they age), has for more than 20 years driven their marketing strategy based on a slogan which states that you never actually own one of their watches, but merely look after it for the next generation [62]. Of course, what the marketing material omits is that every few years, their products should be serviced by a skilled watchmaker (who is "authorized" to have access to the necessary parts and tools), and a *collection* of equally functional watches can be bought for cost of each service alone. As such, the lesson for interaction designers here is that *perceptions and relationships of similar nature can be induced in the context of digital artifacts with appropriate design and presentation.*

The second point that we wish to make via this exemplar is that there is a *market* for products of extravagant design, where profound technological obstacles may be challenged towards seemingly insignificant ends (e.g. key management for blockchain applications); and the economics of this market are not subject to the same forces that drive the markets for disposable consumer electronics. *Cost is not a constraint in the market for heirloom-quality artifacts.* For designers, engineers, and craftspeople, this translates to a world of opportunities. One example: Figure 6 depicts the "H8 - Flying Sculpture," known as "the watch that does not tell the time." It is intended to function as a piece of mechanical jewelry, showcasing a sophisticated mechanism known as a "tourbillon." Watchmaker Beat Haldimann currently offers each piece for a retail price above 150,000 Swiss francs, excluding any taxes. For a slightly *higher* price, Haldimann also offers the "H9 - Reduction," which is mechanically a very similar design, but different in that it is covered with a completely opaque, black sapphire front, so *the mechanism inside can never be seen*. This is one among many examples of luxury wristwatches exchanging hands for remarkable monetary value, for reasons which may bewilder the lay observer. However, the phenomenon of luxury artifacts becoming more desirable as their price increases has been studied in economics, where such goods that contradict the basic laws of supply and demand are known as *Veblen goods*, after the economist Thorstein Veblen who has pioneered the analysis of purchasing and consumption behaviors [95]. The implication here is that high cost is

Figure 6. The "H8 - Flying Sculpture." (©Valentin Blank, courtesy of Haldimann Horology.)

not an issue, and may even be an advantage, in the market for aesthetically pleasing and long-lasting mechanical mobile devices. As such, it is not entirely unreasonable to expect that the potentially high costs of developing technology that can offer sound cryptographic key management solutions in mobile devices can be recovered in the market.

DISCUSSION

This section exposes some of the critical limitations of the design direction we are proposing, and the open questions around those issues. In doing so, for designers and developers who wish to create robust interactive systems that are intended to last multiple human lifetimes, we reveal additional design resources for further reading.

We acknowledge that our proposal comes with important limitations with regard to human factors. First and foremost, as Odom et al. (2012) have noted, "the notion of 'designing an heirloom' is contradictory. The ways in which an object achieves heirloom status is highly idiosyncratic and heterogeneous." An artifact that one owner cherishes as an heirloom may find itself in the hands of a different owner, under different circumstances, who will not think of it as such [67]. As such, we acknowledge the value of incorporating fashion perspectives in the design of long-lasting artifacts, which emphasize the time-dependent, intersubjective aspects of aesthetics [71, 72, 73, 74, 75]; along with approaches that primarily regard the user experience as a dynamic phenomenon that changes over time [45, 46]. Experiments with design philosophies centered around incomplete, broken, and changing media and "graceful aging" can also serve to inform such design efforts [34, 81, 84, 90].

With regard to persistent data, ethical and design issues of curatorial authority come into play [48, 67]—as termed by Odom et al. (2010) as the "the burden of unfiltered contents and collections" [69]. While we have so far considered the transfer of ownership and value primarily through the lens of economics, the subtleties of human relationships cannot be disregarded. In many cases, the subject of ownership transfer in the case of cherished and/or inherited objects is intertwined with complex issues such as bereavement [57, 69] and changes in self-conception [6], which must be handled with care.

A salient property of the blockchain as a design material, one which is highly significant for heirloom computation, is that entries on the blockchain cannot easily be deleted or altered. As such, in addition to human factors, in certain cases, legal issues must be navigated. In an age where the "right to be forgotten" on networked digital media is being discussed as a fundamental right [19, 82], it is possible that the legal backdrop of the future will necessitate the design of "forgetting as a feature" [3]. Will it then be the case that we will consider the blockchain to be a *hazardous material*?

A further complication is that the persistence of the data in a distributed system is tied to the collective actions of many agents with different intentions and incentives. Once designed, the rules that govern the behavior of blockchain-based software are not trivial to change. Making updates to the workings of a blockchain-based system often turns into a tangle of complex political and human factors issues.

Documentation is another significant issue in the case of a systems meant to last for generations. How will the features and properties of the system be communicated to users in a future-proof fashion? Here, rather than conventional notions of documentation and the communication of affordances in computing and product design [31, 65]; it makes more sense to draw from design efforts dealing with long-term, consequential topics. One example can be the principles that guide the design of signage used to indicate sites for nuclear waste storage [89].

While we have so far advocated for considering purely mechanical artifacts as an enduring physical manifestation of computational heirlooms, it is a fact that the interactivity afforded by a durable, mobile, mechanical artifact will not be on par with current mobile device offerings. However, there exist a wide variety of domains where engineers routinely deal with extreme requirements for electronic devices, in relation to durability and lifespan. Know-how from these domains can be leveraged towards electronic solutions. First, implantable medical devices come to mind. The inside of the human body is "an extraordinary environment to the engineer" abound with electrical, chemical, and mechanical reactions – any electronic devices that must function in this environment must be designed to effectively cope with challenges in "biocompatibility, hermeticity, structural design, delivery system, power management, detection, and wireless communication" [40]. Designers and engineers may tap into resources that document the development of such systems (e.g [21]). Further examples of such extreme engineering contexts are scientific equipment, and mission-critical military, power, and space exploration technologies [97]. Drawing on extreme engineering practices, materials, and designs would come at a prohibitive cost in the context of the economics of ordinary consumer electronics, but we can reiterate that the economics of artifacts intended to become heirlooms can be fundamentally different.

CONCLUSION

One of the aims of this paper has been to contribute provocations and resources for design and debate around the diametrical notions of *permanance and disposability*, *the digital and the physical*, and *symbolism and function* in the context of interaction design. Drawing on Mubin et al.'s agenda for "sci-fi inspired HCI research" [61], and invoking the notion of *research for design* [24, 26, 102], we have tried to accomplish this aim by by exposing visions, requirements, inspirations, and hypotheses to inspire and inform subsequent conceptual, technological, and scientific work. As such, the intention has been to provoke more questions than we have answered: Can we design and make digital artifacts that have enduring and transferable value over the long term? How can enduring symbolic value and "values" be embedded in digital materials? What design possibilities will be revealed if we radically reconsider how we conceptualize the notion of *material*? How will our design and consumption practices be affected if we foreground rapid wearout as an intrinsic property of electronics? What will the economic landscape look like for designers and manufacturers who aim to defeat the affliction of electronic wearout? What kinds of concerns gain priority when a data-driven product is meant to have multiple owners?

In the course of this exploration, we have identified and articulated a specific design direction, which we can summarize as follows: The user experience in blockchain-based software, or more generally, in distributed systems and cryptographic applications, is a nascent topic of study where further exploration can be fruitful, in terms of inspiring and informing novel designs (e.g. [101]). In particular, adopting Forlizzi and Batterbee's (2004) terminology, we motivate further work adopting "interaction-centered" approaches to the topic, particularly those that foreground "expressive" aspects of interaction [22]. Building on the interaction-centered approach, and based on existing research on sustainable interaction design, product attachment, and ownership transfer, we call for investigations on tangible devices to address this challenge. Materials and mechanical systems that can be used to store and process cryptographic keys in mobile form factors without electronic circuits are an extreme example to this, and likely not to be realized in the foreseeable future. However, reductions and variations of this concept can lead to more feasible artifacts.

As a final note, we must disclose that part of our motivation to advance the notion of heirloom computing stems from vanity. Our observation is that currently, contrary to watchmakers, *engineers, designers, and craftspeople of digital artifacts seem to be prohibited by their materials from embedding their achievements in artifacts that are held to be simultaneously precious and enduring—i.e. "ensouled."* That is to say, despite being genuine monuments to human ingenuity, most computing artifacts are seen as disposable commodities by consumers [9, 32, 67]. This work is intended as a stepping stone on the way to overcome this limitation by offering the requisite motivation and scaffolding.

ACKNOWLEDGMENTS

The first author thanks his lifelong friend Ozan Bozkurt for the inspiration and designer Özgün Kılıç[7] for contributing visuals; along with his father, Can Baytaş, who almost 50 years ago procured a wristwatch that is still being worn daily by the son. The last author was partially supported by the Wallenberg AI, Autonomous Systems and Software Program (WASP) funded by the Knut and Alice Wallenberg Foundation. Language consultation by Barrie Sutcliffe.

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