Making Sense of Blockchain Applications: A Typology for HCI

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ABSTRACT

Blockchain is an emerging infrastructural technology that is proposed to fundamentally transform the ways in which people transact, trust, collaborate, organize and identify themselves. In this paper, we construct a typology of emerging blockchain applications, consider the domains in which they are applied, and identify distinguishing features of this new technology. We argue that there is a unique role for the HCI community in linking the design and application of blockchain technology towards lived experience and the articulation of human values. In particular, we note how the accounting of transactions, a trust in immutable code and algorithms, and the leveraging of distributed crowds and publics around vast interoperable databases all relate to longstanding issues of importance for the field. We conclude by highlighting core conceptual and methodological challenges for HCI researchers beginning to work with blockchain and distributed ledger technologies.

Author Keywords

Blockchain; Distributed ledger technology; Bitcoin; Trust; Identity; Typology;

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

As HCI has grown and matured as a field, its scope has extended far beyond the user interface. We now ask more fundamental questions about what the design and socio-technical assemblage of new technologies means for 'being human' [22,62], and the ways in which technical infrastructures shape, and in turn are shaped by, social and cultural phenomena. These are questions of experience, politics and human values [11,19,79]. In this vein, this paper discusses the role HCI researchers, and designers, can – and should – play in the study and development of blockchain technologies and related distributed ledgers.

A blockchain, of which Nakamoto's Bitcoin Protocol [49] was the first and most popularized example, can be described as a combination of three powerful technologies: a *distributed ledger*, a database shared between multiple actors who are all allocated read and write permissions; *immutable storage*, where changes to the ledger, or transactions, are stored in 'blocks' and where each copy of the database retains every block in the 'chain' as an immutable history; and *consensus algorithms*, which are protocols for trustless actors in the network to verify the transactions made on the blockchain, and which achieve a secure, shared consensus about the state of the database. Most famously, these three core features have supported cryptocurrencies, primarily Bitcoin. However, of late, there has been a proliferation of blockchain-based applications. Proponents of blockchain view the technology as utterly transformative, comparable to the Internet in its potential scope and impact [1,32,75,78]. Proposed applications include crowdfunding, payment services, voting, copyright management, supply-chain tracking, authentication services and distributed, autonomous organizations. All of these applications concern elementary issues of establishing online identity, managing online data and privacy, and peer-to-peer online collaboration, underpinned by decentralized, algorithmic governance. As such, blockchain technologies and their emergent application areas all speak to a broad set of longstanding topics of interest for the HCI community.

While many of the challenges related to blockchain technologies may be perceived as technical, or deeply infrastructural, these technologies have the potential to profoundly impact human experience. HCI researchers are increasingly pursuing research funding for blockchain-related projects and, in our own experience, starting to grapple with the hyperbole, implications and place of human interaction and agency in relation to this technology. In this spirit, we set out to produce the first detailed mapping and examination of applications of blockchain technologies to chart the space for HCI and raise implications, issues and challenges for future research. To do so, we have undertaken a qualitative survey of more than 200 emerging blockchain startups, projects and

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applications. From these we develop a typology to distinguish broad classes of blockchain applications, and their distinctive features. Finally, we discuss these to distill human challenges for HCI researchers and designers.

REVIEWING BLOCKCHAIN

There are several technically focused reviews and summaries of blockchain technology (e.g.[21,70,71,75,80]). However, the elemental innovation of blockchain is put forth by web pioneer Marc Andreesen [1]:

'...for the first time, a way for one Internet user to transfer a unique piece of digital property to another Internet user, such that the transfer is guaranteed to be safe and secure, everyone knows that the transfer has taken place, and nobody can challenge the legitimacy of the transfer. The consequences of this breakthrough are hard to overstate.'

Andreesen locates the innovation in the transfer of unique digital property (e.g. currency, data, assets, certificates etc.), which previously would have relied on one or several third-party intermediaries. Much of the hype generated by blockchain stems from this potential to disintermediate and decentralize long-established modes of business and governance. In a wide-ranging review, Werbach [75] describes the promise as 'trustless trust'; it makes '*certain activities trustworthy without the need to trust anyone in particular'* [p.9]. In addition to these 'permissionless' blockchain protocols like Bitcoin, Swanson [70] describes the development of private, 'permissioned' ledgers, (e.g. Hyperledger), designed to support more secure, auditable transactions between verified, private nodes, such as banks.

Reflecting blockchains' rapidly developing nature, Swan [69] (writing in 2014) posits three evolutions. *Blockchain 1.0* describes cryptocurrencies like Bitcoin, affording the transaction of digital property. *Blockchain 2.0* describes more complex interactions, the creation of new decentralized economies and financial instruments, based upon 'smart contracts' – code which is written into and executed on the ledger. The 'Ethereum' platform, developed in 2015 provides such functionality. Finally, *Blockchain 3.0* imagines the diffusion of blockchain technology, and decentralized principles of governance and justice throughout society. Such typologies, and the scope of potential applications, show blockchain technology as a moving target. There is considerable ongoing technical development, extreme volatility in cryptocurrency markets, and politically charged debates about competing visions for a decentralized future [10,27,33].

There are few formal mappings of emerging blockchain applications. Werbach [75] proposes three areas where blockchain has taken root: finance, proof-as-a-service, and decentralized applications. Kane [32] provides a rare, more comprehensive survey of blockchain applications, drawn from start-up investment websites. Working in the field of economics [e.g., 39], Kane maps the domain of blockchain applications to Swan's typology and categorizes most applications as belonging to Blockchain 2.0. Kane's work is a useful reference point; however, our own qualitative survey of blockchain applications looks beyond investor websites and start-ups to include, for example, government-led and academic projects. Most importantly, the analysis of our survey is uniquely oriented to identifying the opportunities for HCI researchers and designers, who are, or may be in the future, designing blockchain applications.

HCI, Bitcoin and Blockchain

There is a small but emerging body of research in HCI concerning blockchain. This mostly builds on a history of work in HCI on money, finance, and peer-to-peer exchange (e.g. [3,8,18,34,37,47,63,72]), but largely concerns the experience, motivations and values of Bitcoin users. Such studies have probed users' and non-users' perceptions of the currency [20]; the experiences of Malaysian Bitcoin users and challenges in designing for trust during exchanges [60,61]; and the cultural affinities of early adopters [36]. Meanwhile, other studies of Bitcoin consider the underlying infrastructure more deeply. Lustig and Nardi study Bitcoin online communities to explore their values and trust in algorithmic authority [42]. Pschetz et al. [57] use the 'BitBarista', an autonomous Bitcoin coffee machine, to probe participants' perceptions of the data transactions in a coffee supply-chain. Jabbar and Bjorn [31] conduct ethnographic work around a Bitcoin ATM business and reveal the inherent materiality (see [33]) in blockchain infrastructure. Notably, they characterize this as an 'information infrastructure', situating their study in the socio-technical work of Bowker, Star and Ribes [58,67,68].

We see our own work as sharing these infrastructural foundations, but taking a wider view in an attempt to anticipate challenges and opportunities for the HCI community. We are particularly inspired in this regard by Dourish and Bell's work [13] in drawing a line from underlying infrastructure (such as ubiquitous computing or blockchain) and its envisioning, to the messy reality of lived experience and human values. In this respect, our concerns here are not exclusively about the politics and power of infrastructure, but also more mundanely, 'where the action might be' [12] – both for the end-user and the HCI researcher. In other words, we hope to ascertain where the work of the HCI community, and interaction designers, begins in mediating and articulating human experience and values when working with blockchain applications.

METHOD

In order to study and analyze the prospective domains of blockchain technology for HCI, we must first develop a corpus of prospective blockchain applications. Reflecting the emergent and hyped state of play, there is no existing public repository of blockchain projects and applications. New startups and projects are emerging in this space on a weekly basis. This therefore precludes a systematic search of a known database of published literature.. Hence this survey (concluded in September 2017) can only be a snapshot, and does not claim to be exhaustive. The purpose of our survey here is to map the functionality of blockchain applications, their heterogeneity and commonalities.

We focused our search on websites for blockchain applications, which returned primarily startup companies. We also included academic and artists' projects, and those supported by governments, the UN and larger corporations. Websites are a primary mode of communication for blockchain projects, particularly those at early stages of development seeking global interest and investment. Such websites provided promotional information about the project, their ambitions, a road map, and often an explanatory, promotional concept video. In many cases, the development team publishes a 'White Paper' that explains the rationale and proposed technical development.

Over a period of several weeks, we set out to create a database of these websites, which we identified from a wide variety of sources. We monitored cryptocurrency news sites and articles,; we followed and used search engines to pursue references in academic literature and white papers (e.g. [70,75]); like Kane [32] we also harvested examples from catalogues of venture capital investments (e.g.[2]). As all of the authors are currently working on blockchain projects we also encountered examples of other applications in our daily work, and catalogued these. In our database we recorded the website link and a short description (around 50-100 words) of how the purpose and functionality of each application was described on its website or in a white paper.

The current viability of projects varied: from proof-of-concept and white papers, to more specific use cases and fully deployed technologies. All appeared active at the time of the survey (though we would assume this will not remain so). Over time, we prioritized heterogeneity. For example, while there are many hundreds of 'alt coins' we sought to catalogue only those that were distinctive or illuminated the domain and design space of 'digital currency'. We also sought to catalogue applications *of* blockchain, rather than applications *for* blockchain. Hence, we have not catalogued cryptocurrency wallets, exchanges, analytics firms, or consultancies and other complementary services. As English speakers, our search is biased towards English-language websites. It is worth reiterating that in many cases, the content of project websites represents a positive envisioning of the technology, rather than any market readiness or real-world application. Nonetheless, through these envisionings we can discern a direction of travel, and the core features and 'promises' of the technology, in order to consider forthcoming implications for human interaction.

Analysis

Once we had collated approximately 100 applications, we began to categorize these. Initially, two of the authors started to generate codes for each project which described the main application domain(s), working from the initial descriptions in our spreadsheet. Where necessary, we delved more deeply into white papers and introductory videos to understand the technology's aim and core features. In this way, we oriented ourselves to the data, with an aim to use these initial codes later on, to produce higher-level themes that described core blockchain applications. Hence, Bitcoin was coded as a cryptocurrency, but also an underlying protocol. Examples of initial codes for domains included copyright management, ticketing services, futures markets, investment funds, IoT and data storage. Following Braun and Clarke [6], we intended this coding, and subsequent themes, as a 'realist' undertaking [p. 9] – an effort to report the current state of play and broad fields of activity for emerging blockchain applications.

We then began grouping related codes and applications thematically: e.g. 'futures markets' and 'crowdfunding' were classed as 'financial services'. As new applications were identified, we continued to add these to the sheet, and refined and iterated any codes and classes as necessary. We also compared our codes with the application classes produced by Kane's earlier survey [32], to sense-check our own coding, and highlight potential projects and domains that we may have overlooked. The result of this analysis produced seven high-level themes that we present below as an overarching typology. The resulting database, of 203 distinct blockchain applications, has been included as supplementary material to this paper[1]. It should also be clear that individual applications may straddle more than one class. As such, these classes may be better considered as a series of 'family resemblances' [76]. To emphasize, we do not intend this typology as an absolute canon, but simply as a way to orient HCI researchers to the opportunities and challenges in working with blockchain technologies.

A TYPOLOGY OF BLOCKCHAIN APPLICATIONS

Application	Description	Examples
Underlying Infrastructure	Underlying protocols, decentralized application ecosystems, IoT architecture.	*Ethereum Blockstack, IoTA*
Currency	Payment services, internal currencies and utility tokens.	*Bitcoin, Dash, Kin*
Financial Services	Asset management, investment trading, and crowdfunding.	*Ripple OpenLedger Swarmfund*
Proof-as-a-service	Notaries, registers and attestation, supply-chain management.	*Blocknotary Chronicled, Everledger*
Property and Ownership	Digital rights management, copyright and ticketing services.	*Creative Chain Blockphase Aventus*
Identity Management	Self-sovereign digital identity, and authentication.	*Civic, Blockchain Helix, Bitnation*
Governance	Voting services, distributed autonomous organisations (DAO's).	*Followmyvote, Backfeed Crowdjury*

Table 1: Typology of seven classes of blockchain applications.

[1] This supplementary database is maintained at: https://doi.org/10.6084/m9.figshare.5765502.v1

Our survey of blockchain applications is described in a typology of seven central applications, summarized in Table 1. We subsequently describe each of these, in turn, through illustrative examples. For clarity, we reference these examples by name only; the web domain of each can be found in the supplementary database. Below we report these examples in sub-domains, which reflect some of the initial coding. We also analyze the key functionality and innovations of blockchain that they rely upon in each case.

Underlying Infrastructure

Blockchain technology is underpinned by an orchestration of supporting hardware and software components that integrate decentralised cryptographic protocols, distributed cloud computing (i.e. processing, storage, connectivity) and development environments to support the implementation and actuation of real-time blockchain applications. The projects discussed in this section are specifically concerned with the development of core foundational infrastructure components to leverage blockchain capabilities across a range of end-user applications.

Blockchain Protocols

The Bitcoin protocol itself has been used as a basis for many other projects and alt-coins. ‘Ethereum’ goes further to provide an open-source, decentralised programmable blockchain framework for developers to create arbitrary ‘smart contract’ applications using a native programming language (‘Solidity’). For example, the ERC20 Token Standard [17] offers a platform on which to create any kind of customizable cryptocurrency or token. Many other protocols, and related architecture, are now emerging that innovate around new models of reaching a distributed consensus. Systems like ‘Hyperledger’ and ‘BigChainDB’, are tailored to financial institutions, focusing mainly on private, permissioned ledgers. The core distinctions between many of these protocols pertain to ‘who one trusts’ to maintain the ledger (e.g. a central authority, known actors, nobody) and what kind of assets (e.g. currency, contracts, physical assets) the ledger records [7].

Decentralized Ecosystems and ‘Dapps’

Beyond the fundamental cryptographic protocol layers, several projects endeavour to build software platforms for a ‘decentralized internet’. ‘Filecoin’ and ‘Maidsafe’ offer platforms for a distributed data storage market where individual computers or smaller networks can rent out unused disk space. ‘Brave’ reimagines ad networks, proposing an *‘attention-based ecosystem of rewards’* between users, publishers and advertisers. ‘Lisk’ and ‘Blockstack’ position themselves as alternative app stores, and a platform for developers of these ‘decentralized applications’ (or Dapps). The ‘Dapp’ vision is epitomized by ‘Status’, a messaging app similar to ‘WeChat’, with many familiar online services (social media, content sharing, games, payment services) built into a decentralized ecosystem. These projects are often framed in terms of contesting centralized monopolies of companies like Google, and Facebook. By side-stepping third parties who oversee the network infrastructure, these decentralized applications tend to emphasize privacy, avoiding censorship, peer-to-peer exchange and community rewards.

Internet of Things (IoT)

A number of projects implement blockchain specifically as underlying software architecture for IoT, with the ambition to make connected devices more interoperable and secure in the sharing and trading of data (e.g. IoTA, Chain of Things, FlowChain). These projects envision connected devices partaking in data marketplaces, which ‘IoTA’ describe as an *‘economy of things’*. For example, IoT sensors could help regulate and connect to a decentralized market for solar energy (e.g. ElectriCChain). Other projects like ‘Slock.it’ pitch their efforts towards the sharing economy, to create a Universal Sharing Network to *‘rent, sell or share’* anything. Importantly, in contrast to purely digital currencies like Bitcoin, these projects claim to connect real-world events and assets to transactions on a blockchain.

Currencies

The original use case for blockchain was as a digital currency, and as a medium of online, peer-to-peer, global exchange. These cryptocurrencies are envisioned as both cheaper, faster and more flexible payment services, as well as a model for programmable currencies and utility tokens.

Payment Services

Bitcoin has spawned numerous cryptocurrencies. Some of these are tradeable assets or network tokens which underpin other blockchain services (e.g. Ether or Ripple). Others are seen explicitly as alternatives to Bitcoin (e.g. Litecoin, Dash, Zcash or Monero), and are envisaged as a medium of exchange. Each emphasize different priorities, such as the speed of transaction, security, anonymity, ease of use or ethical application (e.g. Faircoin).

They share some important features: a secure means for digital payments; theoretically with low transaction fees; and without the necessity of intermediaries, such as PayPal. A distributed ledger maintains the balance of each ‘wallet’; each transaction between wallets is then stored in a blockchain, preventing fraud. Since these transactions occur outside of regulated banking sectors they can afford anonymity. Decentralized, e-commerce applications may both accept cryptocurrency as payment, but also support private, and censorship free, exchange (e.g. Particl, OpenBazaar). Such services propose to automate much of the governance and payment processing services (typically undertaken by a third party), and support a global marketplace. However, while underlying protocols like Bitcoin have proved remarkably robust, attendant infrastructures that mediate many payment services, such as cryptocurrency exchanges and wallets, have frequently been the target of hacks and fraud. As transactions are irreversible, there is little protection for users in these cases. Further, the price volatility of cryptocurrencies, especially Bitcoin, can see them become investment vehicles and a store of value, rather than a medium of exchange.

International Payments
Cryptocurrencies are proposed as a significantly cheaper and faster alternative to international payments and bank transfers. Applications such as 'Bitpagos' or 'BitPesa' seek to leverage this on a regional scale towards becoming a payments solution across Latin America or Africa. For example: by connecting importers and exporters or supporting a common currency for travel booking. Such services may also provide alternative forms of banking to the unbanked (see 'Banqu'), or where there is considerable distrust in existing financial institutions. The potential ease and low transaction fees for international payments is attractive to aid and development programmes. Startups like 'Disberse' propose to use cryptocurrency to distribute and track development funding much more directly, avoiding exchange rate costs and intermediaries.

Micropayments
Cryptocurrencies are also divisible and fungible (any coin can be exchanged for another); when combined with very low transaction fees, and algorithmic transactions, these can support micropayment models. 'Satoshi Pay' describes itself as the 'pocket change' of the web. These cryptocurrencies may support new business models by monetising novel interactions (e.g. viewing seconds of a video or advert (Brave); tipping an online performer (Kin)) as alternatives to ad-revenue for content creators, reflecting visions for a metered internet. More broadly, small amounts of cryptocurrencies may be presented as a donation, reward or bounty payment for certain actions on a network.

Utility Tokens as Internal Currencies
Micropayments relate closely to the wider use of cryptocurrencies as utility tokens. Utility tokens function as internal currencies that can be used to govern participation and access services on a particular network. For example, messaging app 'Kik' has launched a social currency 'Kin', through which users will be able to earn and spend on its platform, based on their interactions. Platforms like 'Ethereum' and 'Waves' offer tools for anyone to set up and distribute their own customisable tokens, and then govern the rules for their distribution and use on their network.

In essence, this suggests new kinds of programmable money [66], with intended values and effects embedded in code. Replicating existing local currency initiatives [25], 'Colu' provides a wallet for a local cryptocurrency in Liverpool. More ambitiously, projects such as 'FOAM' and 'Geocoin' [50] attach cryptocurrency wallets to spatial co-ordinates, setting value and financial rules onto places, such as a toll or bounty for spending time in an area.

Financial Services
So far we have discussed applications and payment services for cryptocurrencies related largely to consumers and small businesses. However, while blockchain challenges the dominance of financial institutions in mediating financial transactions, there are also opportunities for the sector. These technology-enabled financial services seek to leverage DLT to replicate many existing features and functions of investment banks more securely, more efficiently, on a global scale, or by making financial services and investments more widely accessible.

Settlement and Clearing
Companies such as 'Ripple', 'Hyperledger' and 'R3' are working closely with financial institutions to support and strengthen existing settlement processes between banks on the basis of a distributed and shared, but permissioned ledger. Such projects envision the trading of any kind of financial assets and products on a blockchain. Permissioned but crucially, *distributed* ledgers are proposed to offer greater security, faster settlement, and increased resilience.

Investment, Speculation and Margin Trading
Several projects focus on creating new opportunities for investment (especially in other blockchain-based projects). Some applications (e.g. Symbiont, OpenLedger), seek to replicate and extend existing financial services to support the decentralised management of cryptocurrency investments. Projects such as 'Augur' and 'Gnosis' offer prediction markets, which replicate and extend speculative 'futures' trading. This comprises a form of betting, where one can create a 'market', to offer a prediction on a common event, for example the result of an election. Other applications (Kraken, Obits) focus on margin trading to take advantage of the high volatility in cryptocurrency and token markets. Many projects propose to disrupt current investment practices and support a wider range of smaller investors through crowd-based venture funding (e.g. NeuFund, Swarm Fund). These projects position themselves as removing intermediaries to investment opportunities, with smaller investors forming peer-to-peer syndicates. As the tokens they invest are exchangeable, they are easily able to liquidate their investment.

Crowdfunding
Many blockchain projects are now funded through so called 'Initial Coin Offerings' (ICO's) or 'token sales'. Through an ICO, startups can raise capital up front, by selling a proportion of the utility tokens underpinning their application or service. This 'cryptoequity' may additionally afford particular governance or privileged service rights. If the service is successful, it is presumed that the value of the token will increase, and reward early investors. While ICO's remain of questionable legality (depending on their status as securities [74]) this extends the rapid growth of equity crowdfunding in new ways that further challenge traditional models of venture capital.

Other applications (e.g. Bitbond) seek to stimulate crowdfunding and personal investment directly by acting as a mediator and escrow, holding the funds until certain conditions have been met. 'Alice' applies this concept to charitable fundraising, only distributing donations to successfully completed projects. In all of these funding and investment models, blockchain is promised as creating a global liquidity pool, by allowing trustless, potentially anonymous peers to collaboratively invest, and securely trade their investments.

Proof-as-a-Service

The immutable ledger produced by blockchain applications is proposed as a cryptographic audit trail, and to provide proof-as-a-service in a range of domains.

Notary, Attestation and Registers

At its most simple, committing data to the immutable ledger of a blockchain can provide trusted timestamping (e.g OriginStamp). For example, a watermark can be embedded in a digital file, which references its position in a blockchain. This replicates the effect of sending mail by recorded delivery without opening the envelope. Clearly such secure timestamping presents opportunities for the proof of patents and copyright (e.g. Binded, Custos, Cognate). Similarly, 'BlockNotary' proposes blockchain as a legal attestation service.

Importantly, stored as a blockchain, these records are tamper-proof. As such, there are applications for registry and certificate services (e.g. Regis). The Swedish and UK governments are investigating the use of blockchain for land registry [26] to enable due diligence and address costly errors in transferring land titles. Other examples include educational certificates, and patents (e.g. Loci). Registry and notary services are a ripe target for blockchain applications, as they represent often dated, institutionalised and easily corruptible legal practices that rely on particular mediators and costly transactions.

Provenance and Supply-Chains

A blockchain can also be used to connect several different potentially trustless actors in a series of notary actions, which can then securely track valuable objects, assets and processes (e.g. Everledger, Provenance, Chronicled). These are permissioned ledgers, dependent on known actors, which might, for example, connect all of the nodes in a supply chain. The ledger can be 'signed' on delivery and receipt of goods. References to any kind of data could be stored, including that from IoT devices (e.g. Chronicled). For example, a connected thermometer, which monitors the temperature of a storage unit, could be used to identify and prove liability in goods spoiled in transit. It is vital that the physical asset is uniquely identifiable and relatable to the data stored in the blockchain. Material configurations, of locks, watermarking or unique tracking devices can ensure this. 'Everledger', an application to track the provenance of diamonds and their certificates, relies on each gem having a unique optical signature.

These principles can be applied to secure all kinds of notary and legal processes, or simply to prove that data exists (e.g. Tierion). 'Factom' proposes blockchain solutions for document management systems, tracking edits and changes to any kind of documents over time. This could support auditing and compliance processes, or the securing of documents in the mortgage industry. Previously, a central regulator might be required to oversee or audit these kind of processes. By transacting through an underlying shared blockchain, a number of actors, with otherwise separate and potentially siloed databases, are able to confirm the authenticity of each others' records, while keeping much of the data distributed and private.

Property and Ownership

The use of an underlying database to track and certify the transactions related to physical and digital objects evidently has implications for managing the rights and ownership of all kinds of property. Especially where ownership is complex (e.g. media rights); retaining value is related to provenance and uniqueness (e.g. art); where re-use is difficult to detect (e.g. piracy), or where existing licensing and regulatory bodies are weak, fragmented or mistrusted.

Copyright

Several services intend to support individuals in creating and enforcing copyright of their creative content (e.g. Binded, Cognate, Custos). Many others go further in creating platforms for the distribution and management of the use of those works (LBRY, CreativeChain, MediaChain, Blockphase). These propose to empower individual creators, both by enabling new monetization models (through for example micropayments based on use/audience figures for their content), but also in challenging the centralised power of traditional copyright management organisations such as record companies, publishers and advertisers. An important distinction here, compared to simply 'proof-as-a-service', is the ability to attach conditions and smart contracts to these forms of digital property. Hence the records, and the obligations they represent, can be managed and enforced automatically.

Ticketing

Ticketing provides a specific example of these new modes of digital ownership. Numerous blockchain start-ups are targeting smarter ticketing services (e.g. GUTS, Aventus, Ticketchain) to overcome fraud and extortionate ticket resale prices. These platforms aim to sell a ticket as unique property, to an identifiable individual (e.g. via a mobile phone or credit card). They can then attach conditions to the sale and resale of that property – for example setting a maximum resale cost and ensuring that a proportion of that resale is returned to the artist or venue.

Identity Management

Blockchain applications may support both individuals and organisations in managing and authenticating identity.

Self-Sovereign Identity Management

Currently, most digital identities are those provided by a third party, for example via a Facebook or email account. In other cases, official, state-backed documents (passports, social security numbers) which are difficult to forge or can be traced through other records are the basis for an identity. Blockchain applications such as Civic, Spidchain, UniquID offer the potential for *'self-sovereign digital identity'* –

where an individual is able to issue and control their own identity. Many of these services are initiated by recording biometrics (e.g. Hypr), such as a fingerprint, or an iris scan, to establish a unique identity. Other personal information such as an email address, bank details and demographics can be attached. Verified providers, for example a shopping or travel booking site can then make requests to the ledger for access only to the specific data they require to facilitate that transaction. As more trusted providers and verifiable claims are made about an identity, this may build a 'web of trust', becoming more reputable, and fraud-resistant. An in-depth review of different models of identity management using DLT is provided by Dunphy and Petitcolas [16]. Notably, while these services leverage aspects of decentralization, they frequently rely on intermediaries. They also encounter familiar challenges and regulation in identity management regarding 'know your customer' (KYC); anti-money laundering (AML); and data protection (GDPR).

Decentralized Sharing of Personal Records

A self-sovereign identity is proposed to make it easier for individuals to manage a single identity, and control and share only specific parts of one's identity, which can be trusted not only by companies, but other peers. For example, to be able to prove one's age, without sharing copies of a passport. Several applications are focused on the implications of this for medical records. The 'Hashed Health' consortium seeks to federate data from multiple healthcare providers. Other applications seek to make it easier for individuals to share specific parts of their health records – for example 'Safe' proposes a service to seamlessly prove clean sexual health to a partner.

Identity and State Services

The notion of self-sovereign identity may present a challenge to governments who typically control and record national identity, although governments (such as Estonia's e-residency scheme) may also begin to use blockchain to verify identity. Notably, self-sovereign identity could offer agency to individuals with precarious state-backed identities. Indeed, the UN is actively investigating blockchain applications for refugees [77] who require a secure identity to access support services. 'Bitnation', a *'decentralized nation',* takes stateless identity to the extreme, by seeking to provide completely decentralized state services, unbound by geography.

Distributed Governance

Applications in previous domains have shown the potential for entities to have new ways of managing identity, to track and own property, and to make transactions with each other. However, more broadly, the consensus algorithms which allow multiple, distributed nodes to reach agreement on the state of the ledger, also create the potential for distributed decision making and governance. Swan [69] describes this move into the field of justice and governance as 'Blockchain 3.0'; Wright and De Filippi [78] remark the rise of Lex Cryptographia, or 'code as law'.

Voting

Voting can be recorded as transactions in a blockchain, with the ledger accounting for votes cast, and avoiding double-spending of votes, much as with currency. Similarly, crowdfunding projects can enact different kinds of market-based governance, 'voting' for specific projects by committing funds. In other examples, votes can be devolved to other users, or allocated automatically, according to certain preferences, as so called delegative or 'liquid democracy' [53]. 'Followmyvote' anticipates such systems will provide greater transparency for national elections, supporting democracy within organizations and local governance, for example in participatory budgeting [66]. In another case, the Icelandic government is investigating 'Social Krona' – a currency which citizens can spend in shops, but which is earned through democratic acts, such as voting and attending town hall meetings.

'Crowdjury' is an even more market-driven project, to support a distributed and transparent judicial system. It provides an online crowd-working platform for the decomposition of the judicial process, from filing complaints and submitting evidence, to receiving a verdict from a randomly selected jury of users. Blockchain offers a trusted shared ledger of these activities, and all of the actions on the platform are compensated with Bitcoin. There is hence a potential tension between activities typically perceived as civic duty, and incentivizing civic participation through economic rewards.

Distributed Autonomous Organizations (DAO's)

Alongside these new models of crowd-work and voting, many blockchain applications anticipate greater algorithmic governance. At their most simple, several applications we have already discussed look to codify and automate existing processes, such as form filling, or settling payments through 'smart contracts'. These are protocols or decentralized applications which automatically execute an immutable, and unstoppable contract, if certain terms are fulfilled.

More sophisticated *smart contracts*, create the potential for distributed and self-sustaining autonomous organizations. 'Plantoids' are artworks which invite donations. Once enough donations have been accrued, a smart contract will automatically commission an artist to replicate the original piece. 'Terra0' more ambitiously imagines an augmented forest that owns and manages itself – when it grows sufficiently, smart contracts will be executed to harvest some of the forest, and reinvest capital to plant new trees.

Distributed and algorithmic governance remains the most ambitious and radical of blockchain applications. Based on series of self-executing smart contracts, 'Aragon', a platform, boldly describes '*unstoppable organizations'*, however their feasible scale is unclear and such projects are predominantly conceptual. Nonetheless, Pschetz et al.'s BitBarista [57], demonstrates the feasibility of objects that behave autonomously, and co-ordinate human interaction through transactions executed by smart contracts.

IDENTIFYING HUMAN CHALLENGES

In the previous section, we have sketched seven broad applications of blockchain technology, with necessarily brief explanations and examples. In this section, we look more analytically, to identify the way in which some of the core features of blockchain entail human challenges, which HCI as a field should seek to address.

Transactions, Tokens and Financialization

A transaction, which writes a new entry to the ledger, is the basic component of interaction with a blockchain. In the case of currencies, transactions are very familiar, in the exchange of money for goods and services. However, many of the applications we surveyed involve the creation and exchange of tokens, and entail a formalization of transactions, in previously informal and unaccountable domains. For example, chat app Kik imagines the earning and spending of a social currency 'Kin' – to set up VIP rooms, tip artists or promote messages. Since such currencies afford microtransactions, any definable activity can become the basis of a transaction. As such, we find ourselves in situations where human activity and interactions with systems become a series of measured and accountable transactions. HCI and CSCW are replete with studies about the politics of such measurement, and the implications of systems which poorly account for, or formalize, the way work and collaboration is actually, and often informally, achieved (e.g. [5,23,55,56]).

There are wider questions about the way in which tokens, and the associated conditions and politics of their circulation, mediate value. Anthropologist Daniel Miller highlights historic examples of the difficulty in reconciling the representation of economic value (e.g. a price) with societal or individual *values*, which are often *priceless* [48]. Miller's conclusion is that any representation of value is most *valuable* when it can be used to bridge between several competing different values, allowing the linking of different worlds – for example enabling the translation of tax receipts into various, valued local services. If we follow Miller's suggestion that an abstract value is most productive in linking diverse worlds, the distributed and programmable potential of blockchain applications appears promising. On similar ground, Ikkala and Lampinen [28] describe how money, in the context of AirBnB, becomes a useful frame to manage network hospitality – it can help select, and control the demand and type of guests who stay. And yet, Miller cautions that at some point, the quantified value has to give way to qualitative values – this seems at odds with the necessary formality of transactions. Ikkala and Lampinen suggest money also leads to *"calculative and instrumental social interactions"* [28, p.1042]. A social currency in Kik, or the trading of IoT data hence resembles a 'financialization of everyday life' [44].

There is therefore considerable work to be done in unpicking the experiences and complex value constellations [65] that blockchain applications can foster, and the way they might formally reflect, embed or enact human values. This seems especially pertinent for blockchain applications that endeavor to support decentralized governance, management of the commons, or digital civics [73].

Procedural trust between new actors

Blockchain facilitates transactions, consensus and shared history between otherwise trustless actors. Hypothetically, this trust is achieved through transparent, codified and immutable procedure. This is trust in the enduring veracity of a technical process, rather than human trust in any individuals or institutions. An immutable ledger can also produce a cryptographic audit trail for retrospective action.

Most significantly, this can afford entirely new interactions between people and things, especially online. These new relationships foster new markets. For example, 'Buy.co' supports distributed, collaborative buying from wholesalers. But it might also point to the potential of platforms for self-organization and political co-ordination, beyond purchasing power. In extremes (e.g. 'Bitnation'), such logic imagines the breaking of state-based institutions and services.

For HCI, there are questions about how to demonstrate and prove such trust to an end user, and how or why blockchain achieves this ahead of an existing mediator? When should we trust the promise of cryptography, or a 100-year-old bank? For example, theoretically, there is potential for much more direct forms of aid and international development (e.g. 'Disberse'), potentially stepping outside the mediation of an international NGO. Which parts of the process would a donor expect to be scrutable in order to trust it? Without a mediator, would a donor expect more control over exactly how their donation was spent, and seek to attach more conditions to it? How would a recipient prove those conditions had been met? Hence while a technical process can be conceptualized, there are challenges in what exactly ends up 'on-chain' (i.e. what is recorded in the ledger), and how this is made transparent, usable and trustworthy?

Federated and Interoperable Data

A feature of several applications we surveyed is the promise to federate databases to make them more interoperable through the sharing of a third-party ledger. Rather than requiring a centralized, and vulnerable or untrusted mediator, a blockchain can govern and make transactions transparent. This is presented as a potential panacea for securely connecting and verifying, for example, IoT devices and online identities. This reflects visions of entities being able to hold their data, attach conditions to it, and share only what it is necessary or desired.

However, the seamless management and effective setting of the conditions about sharing of ones data is clearly not trivial. Although an advance on currently opaque terms and conditions [41], how well will people be able to understand or predict the implications of sharing their data, or formulate rules (smart contracts) about their preferences?

Even more fundamentally, it is not yet clear what it would mean for people to 'own' the data produced about them, and enter into exchanges with devices and algorithms.

Furthermore, while welcoming mechanisms to combat identity fraud or misuses of private data, what room is there to change or flex the conditions, and enjoy a plurality of identities? People employ many different identities online, which they may wish to keep extremely separate. How would such a system contend with a 'right to be forgotten'?

Lastly, this also suggests a further complication of the 'grammar of action' [24] that someone might undertake in relation to their data and digital possessions. While the notion of ownership of digital things has been seen as 'lost in translation' [52], blockchain provides new ways for individuals to assert their rights and conditions on them. HCI might investigate further what these conditions might look like, and how empowering interactions might be developed around them.

Harnessing Crowds and Publics

Through transactions, procedural trust, and interoperable data, blockchain applications can facilitate trustless and distributed peers to collaborate in crowd work, and challenge existing centralized models of governance. Many blockchain applications are economically and incentive driven, supported by micropayments of a native token. Global prediction markets, which speculate and report on real-world events, view themselves as producing 'crowd-sourced wisdom'. Many of the existing challenges for crowd work [35] apply equally to blockchain applications. For example, the satisfactory decomposition of tasks on 'CrowdJury' seems problematic in relation to the real, and more holistic work of current legal professionals. Blockchain applications suit market-driven crowd work, as individuals follow a transparent process, share a common ledger, and tokens can be awarded for reputable actions.

However, through the organization and co-ordination of previously trustless actors blockchain applications may also lead to the formation and self-governance of 'paying publics' [38] around common resources or concerns. Replacing mediators, and supporting crowdfunding or voting via tokens as alternative modes of decision making, encourages the imagination of flatter, more decentralized and potentially locally democratic organizations.

For both crowds and publics, the distinctive value of blockchain appears to be in a push towards algorithmic governance, underpinned by economic incentives. Most ambitiously, these distributed organisations could be significantly autonomous, with members of the public holding tokens or equity in a self-maintaining DAO [51].

DAOs offer some of the most exciting opportunities and alternatives to current economic and governance models, but there are serious questions about how human oversight might be embedded and maintained. Acting 'autonomously' hints at breaking away from traditional centralized power, but how autonomous should such organizations be? How (and who) is held responsible for their actions? While DAOs might pertain to large scale governance, the autonomous BitBarista [57] affords hyper-local governance, at the scale of a coffee cup, as users vote for the source of coffee beans for their next cup of coffee. Still, how is the BitBarista responsible for its actions in the world, and who might oversee its proper interaction?

Gateway Services as Mediators

These prior implications have been predicated on end-users being able to directly interact with distributed ledgers, smart contracts, tokens etc. with limited discussion about the interfaces which mediate such interactions. Clearly such interfaces are crucial, and one would expect these to be part of the natural domain of HCI and UX researchers. Much of the existing research on Bitcoin has been focused on interactions with cryptocurrency wallets and exchanges. Notably, these applications are often not decentralized, and have been sources of fraud (e.g. MtGox), but also occasionally recourse. The most ardent proponents of blockchain imagine an entirely decentralized future without needing to trust any third-party. HCI should consider carefully the role and design of any mediators; as sometimes it may be necessary to strongly advocate for particular accountable roles.

There are particular implications surrounding which interactions or transactions happen 'on-chain' (and are recorded immutably), and which can happen 'off-chain'. The size and nature of data stored in a blockchain (on-chain) is a technical limitation on the scalability and speed of transactions. But besides this, we should ask what data really needs to be stored in an immutable ledger, and how this can be elegantly achieved. Returning to the example of more transparent aid-funding, what would donors require, to feel that their donation had been appropriately disbursed? How far could or should one expect to track the economic value of a token, before it is liquidated and taken off-chain? And how would this 'trust' be designed into, for example, an aid-giving app?

Finally, HCI should be alert to the development of gateways and platforms that will make blockchain technologies more widely available and useful to end-users or organizations. Platforms like 'Waves', which could make the distribution and tracking of custom tokens trivial for individual users, or the ecosystems of messaging apps like 'Status' are intriguing for the glimpses they give of potential interaction paradigms for blockchain.

HCI AND BLOCKCHAIN GOING FORWARD

Through this discussion, and allied to the preceding typology, we hope to have motivated a role for HCI in the research and development of blockchain technologies. At the very least, we hope to have contributed to a growing understanding of the wide ranging implications of these technologies. It is evident that technical complexity, rampant hyperbole, and political envisioning make this an area that requires interdisciplinary approaches, in which HCI is uniquely positioned. To conclude, we present four conceptual and methodological challenges we suggest that HCI researchers would be well placed to address.

(1) Holding Blockchain Technologies to Account: In recent years, there has been a wide acknowledgement of the need for algorithmic accountability [43], particularly with the rise in AI, Machine Learning (ML) and algorithmic governance [54]. Blockchain is arguably the vanguard of algorithmic governance, and code as law. We suggest that a key role of human-centered and socially-minded HCI researchers will be to interrogate the ethics of blockchain technology, by studying and holding applications to account as they move from envisioning to essential infrastructure.

Many of the potential ethical challenges are familiar. What biases will be encoded into blockchain code? Who are blockchain applications for? Who do they empower and who is left at the margins? A recurring critique of AI and ML is their tendencies to conform human activities to a machine-like view of the world. The formal transactions of a blockchain may suffer from the same logic.

However, blockchain technology stands out precisely for its claims of complete transparency. Yet, while for example Bitcoin and Ethereum's ledgers are public and immutable, are these truly auditable and scrutable by regulators or end-users? When is such transparency idealistic or inadequate? [46] What power do the core developers and foundations developing these protocols hold? One role for HCI could be to develop tools to support the scrutiny and accountability of blockchain technologies in the way that the Turkopticon [29] might hold Amazon's Mechanical Turk to account.

(2) Engaging Participants with Blockchain: Beyond the study and critique of blockchain applications, HCI could also hope to seriously engage participants in understanding and contributing to the design of blockchain applications.

Such efforts may begin as knowledge exchange and outreach, but should aspire to forms of Participatory Design [59,64]. The fundamental complexity of blockchain makes this a daunting challenge. Maxwell and Speed [45] have pioneered the 'BlockExchange' workshop using lego and resource cards as a tangible introduction to blockchain. HCI might look at more specific methods which distil key applications such as distributed governance, or notary services. Speculative methods could also be employed to explore and enact the implications of potential blockchain applications with users. In particular, HCI researchers might look to working with industry, third sector and civic groups who manage resources and govenance in an effort to uncover unique use cases, and look beyond the investor driven applications prevalent in our present survey.

(3) Designing with Blockchain: There is very little guidance or research on how to design with blockchain, or which consider the infrastructure, or its features as a design material. Dove et al. [14] point to the problems posed for UX practictioners when simply 'applying' ML, and where the user experience is absent from the conception of an ML-driven application. HCI could look to develop templates and design patterns for different blockchain applications, and produce strong case-studies in different domains. More creatively, we might look at how to do ideation, prototyping and envisioning work for blockchain applications, which spans disciplines, and takes in their technical, economic and governance features.

(4) Expand the Imagination of Blockchain Applications: Finally, as so many of these visions remain immature or conceptual HCI researchers have an opportunity to expand the imagination of blockchain applications, which are currently overwhelmingly driven by a mix of engineering, investment and crypto-anarchist visions. There are radical possibilities at the heart of blockchain, but in practice, many of the examples we catalogued simply extend current market-driven dynamics into new territories, with much greater automation. Researchers would do well to consider blockchain in novel, unprofitable contexts, working with diverse and marginalized groups, or for public services. While we see Participatory Design as vital in this enterprise, we should also recognize the value in more radical and speculative design-led thinking [4,15]. Taking on the politics of many current envisionings of blockchain, we also hope HCI might take inspiration from artists working in the area [9,40], and engage in more critical activities, undertaking forms of adversarial design, and considering the design of 'critical infrastructure' [30].

CONCLUSIONS

This paper presents a detailed mapping and examination of emerging applications of blockchain technologies, in an effort to chart the space for the HCI community. We present a typology of seven classes of blockchain applications: underlying infrastructure; currency; financial services; proof-as-a-service; property and ownership; identity management and governance. We propose that these applications present some fundamental human challenges, related to financialization, procedural trust, algorithmic governance and the front-end interactions with such an infrastructural technology. As the HCI community develops a better understanding, we encourage researchers to hold blockchain applications to account, find ways to engage and design blockchain with participants, and expand the current imagination.

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