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Self-Sovereign Identity in a Globalized World: Credentials-Based Identity Systems as a Driver for Economic Inclusion

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After introducing key concepts and definitions in the field of digital identity, this paper will investigate the benefits and drawbacks of existing identity systems on the road toward achieving self-sovereign identity. It will explore, in particular, the use of blockchain technology and biometrics as a means to ensure the “unicity” and “singularity” of identities, and the associated challenges pertaining to the security and confidentiality of personal information. The paper will then describe an alternative approach to self-sovereign identity based on a system of blockchain-based attestations, claims, credentials, and permissions, which are globally portable across the life of an individual. While not dependent on any particular government or organization for administration or legitimacy, credentials and attestations might nonetheless include government-issued identification and biometrics as one of many indicia of identity. Such a solution—based on a recorded and signed digital history of attributes and activities—best approximates the fluidity and granularity of identity, enabling individuals to express only specific facets of their identity, depending on the parties with whom they wish to interact. To illustrate the difficulties inherent in the implementation of a self-sovereign identity system in the real world, the paper will focus on two blockchain-based identity solutions as case studies: (1) Kiva’s identity protocol for building credit history in Sierra Leone, and (2) World Food Programme’s Building Blocks program for delivering cash aid to refugees in Jordan. Finally, the paper will explore how the combination of blockchain-based cryptocurrencies and self-sovereign identity may contribute to promoting greater economic inclusion. With digital transactions functioning as identity claims within an ecosystem based on self-sovereign identity, new business models might emerge, such as identity insurance schemes, along with the emergence of value-stable cryptocurrencies (“stablecoins”) functioning as local currencies.

Keywords: blockchain, self-sovereign identity, migrants, credentials, digital identity

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INTRODUCTION TO IDENTITY MANAGEMENT SYSTEMS

In this section, we will introduce a set of principles and terminology relevant in the identity space, particularly as applied to technologies used to implement identity management systems such as web standards, cryptography, blockchain ledgers, and cryptocurrency applications.

Preliminary Definitions

There is currently much confusion in the identity space with regard to specific core terms such as “identity” and “identifier,” “attributes” and “persona,” which are often used interchangeably and ambiguously, without properly defining the meaning and scope of each term. We provide here a preliminary distinction between these terms, along with a tentative definition that will be used in the remainder of this paper.

An “**identity**” has been defined in different manners, depending on the field of endeavor. In psychology, it is generally used to refer to all the psychological traits of a person, inclusive of the personality, beliefs and other personal attributes (Strohming et al., 2017). In sociology, it includes the culture, history, religion and tradition that an individual is part of Côté (1996). From a legal standpoint, an identity can be associated to the concept of a “natural person” (i.e., an actual human being), or a “legal person” (which might refer to a company, a trust, a partnership, or another collective of people identified as a single person under the law).

For the purpose of this paper, we use the terminology of “identity” to describe all attributes of a person that uniquely defines the person over the course of a lifetime, providing sameness and continuity despite varying aspects and conditions. As such, we distinguish between the notion of “*numerical identity*” which describes the relationship that holds exclusively between a thing and itself¹, and the notion of “*qualitative identity*” which merely describes the properties that different things have in common (Garrett, 2002): only when there is total qualitative identity between two things, can these two things be regarded as being numerically identical.

Yet, even in the context of numerical identity, it is important to note that the attributes of an identity can evolve over time. Identity formation is an ongoing process, whereby a person’s identity is developed over the course of the years, and constantly evolves as a result of the interactions with the person’s environment (Eakin, 1999). Accordingly, identity is dynamic and multifaceted, and every identity management system must therefore be designed in such a way as to be sufficiently flexible, resilient, and dynamic to accommodate the variable and complex nature of human identity. However, regardless of the sophistication of these systems, no identity management system will ever be able to categorically capture all aspects of one’s identity. Indeed, insofar as we attempt to design a system to manage and categorize a variety of different identities, it is

¹As its name indicates, numerical identity describes the relation through which things can be counted: x and y can be counted as one only if they are numerically identical (Geach, 1973).

important to understand from the outset that such categorization will necessarily be a reduction of the specific facet or use case of each identity it comprises².

A “**persona**” is a specific facet of an identity that is expressed in a particular context. While the identity uniquely defines a person, the same person can hold multiple personas, depending on the social context that is taken in consideration (Suler, 2002). For instance, Alice might be a dedicated mom for her daughter, and a loving wife for her husband. She might be a trusted friend to some of her peers, and strict manager to her employees. All these personas are part of the same identity but might display slightly modified features or psychological traits. From a technical standpoint, they can be described as pseudonyms or practical identities (Christman, 2013). While an identity is an abstract concept that relates to the individual as a whole, a persona is a crucial component of any identity management system, because it relates to the way in which individuals “authenticate” themselves to the system (Toth and Subramaniam, 2003).

An “**attribute**” describes an essential, definitional property of a person that qualifies it as a member of a given set (or class) of persons. As such, an attribute is generally not unique to that person. Each person can have an indefinite number of attributes: elements like gender, height, weight, handicaps or capabilities which are inherent to the person, or elements like nationality and citizenship, which have been assigned (and could potentially be revoked) by a third-party, with a view to distinguish or organize people into specific categories (e.g., U.S. vs. French citizens). Of course, most of these categories are abstract classes that can be arbitrarily defined, even if they refer to an inherent property. Consider the attribute of having “red hair” that qualifies a person as part of the red-hair people set. Clearly, it is a natural, non-revocable attribute, yet the class of red-hair people is somewhat arbitrarily defined (what is the exact shade of red that qualifies someone as such?). Similarly, the “gender” category which had been for a long time limited to “male” or “female” is recently being expanded with the advent of people who identify as “non-binary.” Finally, one of the key characteristic of attributes is that, because they are intended to classify an entity into a particular category, they are not unique to it: multiple entities may share the exact same attributes.

An “**identifier**,” conversely, is not intended to describe or qualify a person, but rather to be used as a “reference” to a real-world identity (or a specific persona). As such, identifiers are often assigned (arbitrarily) by a third-party, with regard to a particular use case or domain (e.g., the legal name of a person, a social security number, or a simple username). In other cases, they can be a particular representation of an observable property of an entity (like fingerprints or other biometric data). It is important to note that both attributes and identifiers are, from a strictly technical perspective, mere data strings that can be used as a means to authenticate a particular individual (or persona). Depending on the domain at hand, the same data string can be used to qualify an entity as a member of a set,

²This is mostly due to the gap that exists between a first person knowledge of self, and a third party knowledge of a person by description (Burge, 1988).

distinguish from members of different sets, or uniquely identify them within a set. Yet, attributes and identifiers differ with regard to their purpose: an attribute (as a “qualifier”) is aimed at classifying people within a particular category, whereas an identifier (as a “reference”) is intended to identify someone within a particular domain. Accordingly, even though some identity management systems allow for multiple individuals to share the same identifier (e.g., many individuals share an identical name), or for one individual to have more than one identifier (e.g., in the case of pseudonyms), in order to facilitate the process of identification and authentication, it is often desirable that an identifier be able to identify a person in a *unique* and *unambiguous* way (Jøsang and Pope, 2005). This requires an identity management system to fulfill at least two basic criteria: (1) no two people should have the same identifier (*unicity*), and (2) no one person should have more than one identifier (*singularity*) in the same domain.

In light of this, most identifiers are comprised of a random string of characters that are unique in a particular domain. These are generally issued by a centralized entity, such as a government agency or administrative body, as in the case of a passport number or social security number; or by a company or organization, as in the case of a bank account or an email address. Centralization, in this context, helps ensure a degree of confidence that the identifier is *unique* (i.e., that the same social security number has not been assigned to two different persons) and *singular* to one identity (i.e., that no one may have more than one social security number).

Alternatively, an identifier can be generated directly by the person, as in the case of a pair of cryptographic keys used to access a cryptocurrency wallet. In this case, *unicity* is guaranteed by mathematics—at least at a very high degree of probability (Schartner and Schaffer, 2005), but *singularity* cannot be guaranteed (i.e., the same person can generate more than one identifier). Similarly, decentralized identifiers (DIDs) are an open source web-based standard, which uses a web address (URL) as the unique identifier that contains or points to public identifying information about the identity subject. The public identifying information linked to a DID may include publicly viewable credentials or attestations, or the public key/address of a cryptocurrency wallet. In this way, DIDs may be used in conjunction with blockchain technology and public-private key pairs (Mühle et al., 2018).

Finally, recent technological advances made it possible to develop biometric identifiers that are directly related to the physicality of a person, as in the case of a fingerprint, iris scan or face recognition. If we discount possible errors and inaccuracies related to the technology (Proença and Alexandre, 2010; Canham, 2018), biometric identifiers are often touted as being both *unique* and *singular* to one identity. However, biometric templates are limited to the extent that even the most sophisticated scanning tools only provide approximate representations (Nagar et al., 2010). This is somewhat mitigated by multimodal biometrics (iris scan, combined with fingerprints, face recognition, etc.) that provide higher degree of rarity (Ross and Jain, 2004). Ultimately, it all depends on the size of a population set (Duta, 2009): given a small population, such

identifiers can be said to be unique—although this creates serious privacy problems (see below for more details on the matter).

The Interplay of Identifiers, Personas, and Key Pairs on the Web

With respect to the Internet, the most fundamental identifier, at the network layer, is the IP address, which makes it possible to route packets from one machine to another, until it reaches the right machine. The IP address does not communicate any information about the machine it refers to (i.e., it is not an attribute of it), however, in some cases, it is possible to link an IP address back to a particular individual or organization, whose identity can be ascertained by the relevant Internet Service Provider (ISP)³.

At the application layer, user accounts and passwords are used to identify specific personas (which may be persons, companies, machines or other entities) interacting on an online service. While these also do not provide, as such, any personal information about the persona, many online service providers require users to communicate additional attributes or identifiers (e.g., real name, age, etc.) in order to ensure that only legitimate individuals can access the service.

Yet, it is worth mentioning that both in the case of an IP address and a user account, only a subset of these identifiers may actually resolve to a natural person. De facto, these identifiers merely refer to a particular endpoint interacting with an online service, but there is no guarantee that this endpoint can be uniquely associated with an individual identity. For instance, an IP address might be used by a multiplicity of persons, and many user accounts are nowadays controlled by bots, rather than persons.

In the context of a blockchain-based system, identifiers are generally managed with public/private key pairs, which uniquely identify the wallet holder (De Filippi and Wright, 2018). Yet, these also do not communicate any personal identifying information about the person, unless additional information is associated with them (Androulaki et al., 2013). Therefore, the same entity (a person, a computer or bot) may own or control multiple key pairs, as key pairs do not necessarily refer to an individual identity. For example, Mary owns a key pair to her Bitcoin wallet, and a different key pair to her Ether wallet.

From a technical perspective, the public-private key pairs are proof of both custody and ownership to any cryptocurrency or tokenized asset held in a particular digital address, or wallet. The private key is necessary to execute transactions to and from the blockchain address identified by the public key. A transaction is not limited to the transfer of a crypto-asset such as a Bitcoin or Ether, but may also represent the transfer or issuance of a cryptographic token through a smart contract transaction (Wright and De Filippi, 2015). An example would be a data access

³The European General Data Protection Regulation 2016/679 (GDPR) states that IP addresses should be considered personal data, to the extent that the ISP has a record of the IP address and knows to whom it has been assigned. See recital 30 of the GDPR, which clarifies “online identifier” as mentioned in the Article 4 definition of personal data: “Natural persons may be associated with online identifiers provided by their devices, applications, tools and protocols, such as internet protocol addresses, cookie identifiers”.

token, which the owner of a dataset (such as a health record or credit history) issues to a third party wishing to access some of the data. The token functions like a key to the datastore, and transactions of that token are recorded on a blockchain ledger to keep track of who has been granted permission and access (Maesa et al., 2017).

In a public and permissionless⁴ blockchain like Bitcoin or Ethereum, which operates without any centralized authority or intermediary operator (De Filippi and Loveluck, 2016), the nodes maintaining the network (e.g., the “miners”) operate without association to a particular given identity (El Haddouti and El Kettani, 2019). In a permissioned blockchain, where a centralized entity or consortium is in charge of identifying or policing the nodes that maintain the blockchain ledger, the key-pairs controlled by each miner are generally associated with real world identities (Hardjono and Pentland, 2019). Reliance on real-world identities provides the additional ability to police (and punish), thereby enabling permissioned blockchains to dispense with some of the security measures that anonymous (or pseudonymous) permissionless public chains must employ, e.g., Proof of Work or Proof of Stake (Shrier et al., 2016). The caveat is that users must trust the governance practices of the central entity or consortium policing the permissioned blockchain (Davidson et al., 2016).

Centralized Identification System Based on Unique Identifiers vs. Multifaceted Web of Trust Claims and Credentials System

As previously discussed, the key tenets of any properly functioning identity system are the properties of “unicity” and “singularity.” Unicity refers to the fact that each identifier is used to uniquely identify one (and only one) individual, i.e., no two persons should have the same identifier. Singularity refers to the fact that each individual possesses one (and only one) identifier in a particular domain, i.e., no two identifiers should refer to the same individual.

Unicity can be achieved without a centralized authority, because mathematical primitives can ensure that no two people get the same identifier, even if there is no central authority to coordinate the identifiers. Each identity provider can issue an identifier using very large random numbers, and even though there is a theoretical possibility that two actors issue the same identifier to different beneficiaries, the probability is so low to be negligible.

In order to fulfill these the singularity requirements, however, most of the existing identity systems rely on a central authority to ensure that each unique and unambiguous identifier is linked to a singular identity (Kulkarni et al., 2012). The centralized authority must collect personal information to ensure the singularity of any given identifier issued into the system. Such a system is generally expensive and bureaucratic, likely politically impractical for the

⁴A “permissionless” blockchain is a blockchain that anyone can join, and where every node is entitled to both read the current state of the blockchain, and add new blocks to the blockchain. A “public” blockchain, conversely, refers only to the ability to read the blockchain, which can be either permissioned or permissionless based on the rights for who may add information to the blockchain.

use case of migrants (especially for vulnerable populations on the move), and subject to high privacy, data abuse, and cybersecurity risks (Whitley and Hosein, 2010). For instance, in 2012, India has launched the Aadhaar identity management system, using biometric data to identify its 1.3 billion inhabitants—many of whom do not have any formal identification (Sarkar, 2014). Participation into the Aadhaar system has become a requirement for Indians to receive welfare benefits, sign up for mobile phones or register at school. However, such a system has raised concerns from civil liberties groups (Jain and Nandakumar, 2012), with multiple lawsuits before India’s Supreme Court whether such a system violates India’s constitutional right to privacy⁵.

Ideally, an identity system should respect the multifaceted nature of identity and look at the different attributes or personas depending on the use cases. Only a small handful of use cases actually require a unique and singular link between an individual and its identifier (i.e., that an individual be identified by a single and unique identifier in a particular domain). This might be the case of voting, whereby a single person should be excluded from voting multiple times under multiple identifiers (Cap and Maibaum, 2001; Alvarez et al., 2009).

An alternative to an identity system based on unique and singular identifiers is a claims and credentials based system (Rannenberg et al., 2015). In such a system, identity is not reduced to an *authoritative* identifier, such as biometric or government issued identification numbers; rather, identity is defined through a network of claims and credentials based on a *web of trust*⁶ authentication (Khare and Rifkin, 1997). Such a system better mirrors the multifaceted nature of human identity, allowing for different *profiles* and *personas* to emerge through a combination of different claims and credentials depending on the use cases. A profile that is appropriate for a loan application may be different than the one used in public forums. While such a system would not necessarily guarantee the singularity of individuals using the system, it would suit a large majority of day-to-day use cases.

THE ROLE OF IDENTITY FOR SOCIO-ECONOMIC INCLUSION

For many years, the World Bank has stressed the need for every citizen to be endowed with a valid proof of identity, as identification has become a necessity for financial inclusion and access to essential services and rights. Specifically, from a

⁵Since 2012, Aadhaar was the object of more than 30 petitions and its constitutionality has been repeatedly challenged in courts. In September 2018, the Indian Supreme Court held that, in spite of these claims, Aadhaar was legitimate, although with a limited scope and restrictions on data storage. For more information, see https://www.sci.gov.in/supremecourt/2012/35071/35071_2012_Judgement_26-Sep-2018.pdf

⁶The “web of trust” concept was first put forth by PGP creator Phil Zimmermann in 1992 in the manual for PGP version 2.0: “As time goes on, you will accumulate keys from other people that you may want to designate as trusted introducers. Everyone else will each choose their own trusted introducers. And everyone will gradually accumulate and distribute with their key a collection of certifying signatures from other people, with the expectation that anyone receiving it will trust at least one or two of the signatures. This will cause the emergence of a decentralized fault-tolerant web of confidence for all public keys.”

development perspective, a recent report of the World Bank⁷ identifies three overarching goals for any identification system:

- **Inclusion and access to essential services such as health care and education, electoral rights, financial services, and social safety net programs;**
- **Effective and efficient administration of public services, transparent policy decisions and improved governance—particularly to reduce duplication and waste;**
- **More accurate measure of development progress in areas such as reduction in maternal and infant mortality.**

Yet, still today, more than 1.5 billion people are excluded from accessing basic services due to their inability to prove their identity⁸. A large majority of these people are located in Asia and Africa, in areas that lack the proper infrastructure to register births and other life events (e.g., in South Asia and Sub-Saharan Africa, respectively, only 39 and 44% of children have births registered⁹) and generally belong to some of the poorest segments of the population.

At the same time, according to the UNHCR¹⁰, there are currently over 70 million forcibly displaced people as a result of conflict or persecution, 25 million of which are refugees—mostly from Syria, Afghanistan, and South Sudan. There are also approximately four million stateless people, who have been denied a nationality, and therefore have been cut off access to basic services and rights. These numbers are expected to grow in the years to come, especially in light of the growing impact of climate change—which has been recognized as a key contributing factor to political conflicts¹¹, and as a significant driver to both internal and international migration¹².

In light of this, the UN has recently launched the ID2020 Alliance¹³, a multi-stakeholder partnership that brings together multinational organizations, non-profits, businesses and government, all geared toward the objective of ensuring that digital identity is responsibly implemented and widely accessible. The goals of the Alliance are twofold: on the one hand, it is in

⁷In 2016, the World Bank's Identification for Development (ID4D) Initiative issued a Strategic framework, recognizing the transformational potential of modern identification systems for the delivery of basic services and rights for the poor. The report is available at the following address: <http://pubdocs.worldbank.org/en/21571460567481655/April-2016-ID4D-Strategic-RoadmapID4D.pdf>

⁸World Bank's 2016 ID for Development (ID4D) report showed that ~1.5 billion people around the world (over 21% of the world's population) cannot prove their identity. See *Ibid*.

⁹*Ibid*.

¹⁰UNHCR, Statistical Yearbook, available at <https://www.unhcr.org/en-us/figures-at-a-glance.html>

¹¹See e.g., Gleick (2014), describing the extreme drought in Syria as a driving factor for the 2011 civil war, and Werz and Conley (2012), associating the success of al-Qaida's recruiting strategies with the overall decline of agricultural and pastoral livelihoods.

¹²The UN's Global Compact on Refugees recognized that "climate, environmental degradation, and natural disasters increasingly interact with the drivers of refugee movements." According to the Internal Displacement Monitoring Centre, there were 18.8 million new disaster-related internal displacements recorded in 2017. While most disaster displacement linked to natural hazards and the impacts of climate change is internal, displacement across borders also occurs, and may be interrelated with situations of conflict or violence.

¹³<https://id2020.org/>

charge of defining the parameters for good and ethical digital identity systems, and, on the other hand, it is responsible for funding and implementing digital identity projects with a social good mindset. Among other things, the ID2020 Alliance has also created a Certification Mark¹⁴, used to label technological solutions that meet the technical standards and requirements established by the Alliance and that satisfy the principles of portability, persistence, privacy, and user-control.

Many proof-of-concepts are currently being developed by public and private institutions to provide digital identity to those currently lacking formal means of identification¹⁵. Yet, when devising these identity solutions, it is important to ensure that one single actor does not hold and control the personal identity records of every identified individual, which may raise significant privacy concerns. In the case of refugees lacking proper identification, in particular, digital identity could be used as a means to identify specific individuals or families which are eligible for cash aid or other type of benefits. Yet, because of the fragility of these populations, it is particularly important to find ways to identify these individuals in a unique and unambiguous way, while simultaneously ensuring that their privacy is protected. This requires devising an identity management system that minimizes the control of one single actor over the personal information of a refugee's population.

Hence, while it remains technology-neutral, the ID2020 Alliance has shown particular interest in blockchain technology, as a possible solution to provide digital identities in a way that is both traceable and immutable, and potentially not under the control of one single company or organization. One of the fundamental requirements defined by ID2020 for digital identities is, in fact, that identities remain portable, and that people retain control over their personal data by choosing with whom it can be shared and for what purposes.

Several non-profit organizations in the humanitarian sector are also involved in the definition of best practices and guidelines to ensure that people dealing with migrants and refugees respect their fundamental right of privacy and data protection. Core documentation has been developed in that regard, including the "Handbook on Data Management" (Blazewicz et al., 2012), the Privacy International's report (2018) on the "Humanitarian Metadata Problem,"¹⁶ and the International Committee of the Red Cross' Handbook on "Data Protection in Humanitarian Action" (ICRC, 2017), which specifically addresses the additional privacy requirements that must be put in place when interacting with vulnerable persons. All these guidelines invite organizations providing humanitarian assistance to take all the necessary measures to protect the personal data of all concerned individuals, while focusing on the core humanitarian principles of "do no harm" and the promotion of human dignity.

¹⁴<https://id2020.org/technical-certification-mark>

¹⁵See e.g., McMullen et al. (2019) analyzing the various blockchain-based initiatives for digital identity, and their various degrees of decentralization and privacy compliance.

¹⁶<https://privacyinternational.org/report/2509/humanitarian-metadata-problem-doing-no-harm-digital-era>

Yet, even if the organization collecting the data respects all of these privacy guidelines, any centralized institution holding such a large amount of personal data inevitably constitutes a single point of failure, which might inadvertently lead to significant data leaks. A true decentralized solution would enable people to maintain full control over their personal data (with a real self-sovereign identity solution), but the lack of a centralized database of identities would make it difficult to guarantee the “unicity” and “singularity” of these identities.

One identified solution to offer a persistent identity from birth, without the need for a centralized authority in charge of assigning a particular identifier to each person, is to rely on biometric data to generate a unique identifier (a biometric hash) associated to every individual. Indeed, in the absence of a centralized authority capable of ensuring that no same person registers twice for an identity, the only way to ensure the singularity of identifiers, without publicly disclosing any sensitive data about the individual concerned, is for these identifiers to be linked to cryptographically-hashed biometric information. This biometric hash can be used as a means of authentication, as it can be verified easily by comparing it with another biometric hash, but it cannot be used to retrieve the biometric information of the individual concerned.

Yet, while such a model is likely to provide important privacy benefits, it comes with the caveat that the singularity of an identifier is inversely correlated with the reliability of the system¹⁷. Indeed, unicity and singularity are a matter of degree: different identifiers with different characteristics may situate themselves on different points on that continuum. While biometric data could be used to create unique and unambiguous identifiers, whether or not they pass a sufficient threshold of singularity will ultimately depend on the degree of technological sophistication and the size of the population (Bhargav-Spantzel et al., 2010; Unar et al., 2014). We analyze below the benefits and the risks of these systems, in order to assess the extent to which they can be legitimately used for the purpose of refugee’s identification and aid disbursement.

BENEFITS AND RISKS OF BIOMETRIC IDENTITY SYSTEMS

Using biometrics as part of an identity management system comes with a few advantages. If people can identify themselves through their biometrics, they no longer need to use passwords

¹⁷Biometric information is normally stored in its raw form, rather than hashed, as hash functions require the exact same input each time. While hashing works well for inputs such as passwords that are exact in nature, biometric inputs are variable by nature; as such exact inputs cannot be guaranteed. For example, an iris photographed under slightly different lighting conditions will produce a different input such that the hashed results do not match exactly. Biometric inputs are compared against templates through comparing the number of stable bits extractable from each biometric scan. While it may be possible to hash a biometric input by reducing the number of stable bits required to the minimum, it would make the biometric authentication less reliable. If the number of stable bits required for a match is increased, reliability is improved; however, it will be more difficult to authenticate given the increased difficulty of achieving the required number of stable bits.

(often weak passwords which are easier to remember but very easy to breach). Insofar as a biometric is difficult to forge (or more expensive to forge compared to breaking weak passwords), biometrics may be relatively more secure than existing authentication systems. However, the use of biometrics within an identity management system may raise significant security and privacy risks, depending on how biometrics are used, stored, and permissioned (Prabhakar et al., 2003). For example, biometrics stored in centralized systems, without mitigating data access policies or security design measures, may be subject to greater security risk than if the data were stored locally on the user’s device (Muller, 2010).

Hence, in recent years, there has been an increasing amount of research and initiatives exploring the use of decentralized infrastructures, mostly based on blockchain technology, to bootstrap new types of self-sovereign identity management systems (Baars, 2016; Jacobovitz, 2016; Tobin and Reed, 2016; Dunphy and Petitcolas, 2018) and combining them with biometrics as a means to ensure the singularity of identities within these systems (Hammudoglu et al., 2017; Garcia, 2018; Othman and Callahan, 2018).

Without going into the merits of these solutions, we describe below the basic operations and procedural aspects of these identity management systems, focusing on the key issues that must be taken into account when designing an identity system that relies on a blockchain-based infrastructure and on biometric information as part of the identification and authentication process.

Decentralized Infrastructure vs. Centralized Custody of Keys

All blockchain-based systems rely on a public-private key pair to record information (including, but not limited to, financial transactions) on a shared and decentralized ledger. Hence, one important aspect of any blockchain-based identity system is who ultimately possesses or controls the private keys necessary to execute a transaction. On that point, an important distinction needs to be made between the decentralized blockchain-based infrastructure, and the mechanism by which the blockchain-based identity system manages the keys associated with each individual entity.

A blockchain is decentralized insofar as its transaction history is immutably recorded and maintained by a distributed network of computer nodes, in order to prevent systemic theft (i.e., rewriting the transaction history to enable double spending). The decentralized nature of a blockchain network does not, however, apply to the custody and secure storage of the keys that control the individual wallets on that network (Hileman and Rauchs, 2017). Centralized control and storage of these keys is a major security hole that explains numerous high-profile cryptocurrency exchange heists. From a purely technical perspective (notwithstanding legal and contractual obligations), ownership of assets on the blockchain is equated with control of the assets, which is managed through the private keys associated with a wallet that contains the assets.

685 To the extent that cryptocurrency exchanges control the private
 686 keys associated with the wallets (or accounts internal to the
 687 exchange) containing customer funds, they also effectively
 688 control these funds, because custody of these keys ultimately
 689 implies full control of the funds stored in that account—much
 690 like physical paper cash (De Filippi, 2014). Hence, because the
 691 customer's private keys were not properly stored and secured
 692 in a decentralized fashion, these centralized exchanges rapidly
 693 became valuable “honey pots” attracting attackers (Gerard,
 694 2017).

695 When marrying biometrics with cryptocurrency, it is
 696 important not to use biometric data as the seed of the private
 697 key unlocking access to cryptocurrency funds. Otherwise,
 698 anyone who can acquire access to an individual's biometric
 699 data would be able to derive that individual's private key,
 700 and therefore unlock the cryptocurrency funds. From a
 701 security and privacy perspective, such a system is more
 702 dangerous than an ordinary centralized cryptocurrency
 703 exchange, as biometric data contain the most sensitive
 704 and immutable personal identifying information (van der
 705 Ploeg, 2003). In short, even if a decentralized blockchain
 706 infrastructure like Bitcoin or Ethereum is used as the backbone
 707 of an identity system (De Filippi and Mauro, 2014), the
 708 security benefits of decentralization do not transfer insofar as
 709 custody of keys remain centralized without mitigating security
 710 design factors.

713 Identification vs. Verification

714 Next, when assessing an identity system, it is important
 715 to identify the types of information that must be provided
 716 at the different steps of the process, as individuals enroll
 717 into a particular identity system, and as they authenticate
 718 themselves within that system. We analyze below the
 719 various steps with regard to a biometrics-based identity
 720 system based.

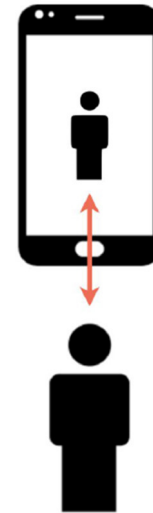
723 Enrollment

724 Enrollment is the process of creating a new user identity
 725 on the biometric system. Each user must provide relevant
 726 biometric samples (e.g., fingerprint, iris, or face) that will be
 727 captured by a biometric scanner or similar device. The collected
 728 biometric data will be used to generate a biometric template and
 729 biometric identifier, associated with personal information (such
 730 as demographic data) for subsequent authentication purposes
 731 (Araújo et al., 2005).

733 Authentication

734 Authentication is the process by which, after individuals have
 735 enrolled into the system, the system checks whether these
 736 individuals have the proper permissions to access a particular
 737 service or to benefit from a particular type of aid, by matching
 738 a new biometric sample against the biometric template created
 739 during enrollment (O’Gorman, 2003). The authentication stage
 740 can be subdivided into two different steps: *identification*
 741 and *verification*.

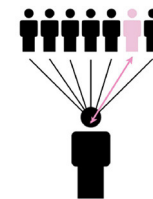
742 Verification



743 Verification is the process of verifying one's identity. It provides
 744 an answer to the question: are you who you say you are? It is a
 745 one-to-one matching process, whereby a new biometric sample
 746 is matched against an authenticated record. This is the case of
 747 using a fingerprint or face scan to access devices like computers
 748 or mobile phones. Currently, the standard practice is that the
 749 biometric record is stored locally and in encrypted format on
 750 the actual device (Schneier, 1999). Thus, neither mobile app
 751 developers nor device manufacturers have access to the template.
 752 The original scan used to create the template for matching
 753 purposes is destroyed, and so are the new scans made upon each
 754 new login, once the matching process is complete (Uludag et al.,
 755 2004).

756 Local storage of the biometric template on the device (rather
 757 than a central server) is a form of decentralized data storage,
 758 which can be further decentralized by breaking the biometric
 759 template into multiple pieces that must come together in order to
 760 be readable. This method protects privacy and improves security
 761 (Zibran, 2012).

762 Identification



763 Identification is the process of retrieving the identity of a
 764 particular individual, based on an identifier. It provides an
 765 answer to the question: who are you? It is a one-to-many
 766 matching process, whereby a new biometric sample is matched
 767 against many templates in an identity database in order to
 768 retrieve the specific identity it has been associated with (Jain et al.,
 769 2007).

770 Ideally, the sample scan should be destroyed once the
 771 transaction is complete. However, the original biometric template
 772 must necessarily be stored on a server, or be otherwise accessible
 773

799 to the operator of the identity system, for matching purposes.
800 Therefore, as opposed to the verification process which can be
801 done locally on a user's device, in the identification process,
802 biometric templates need to be accessible online. In order
803 to minimize security risks, it is thus important to identify
804 mechanisms for secure decentralized storage and processing
805 of data (Ganapathy et al., 2011), such as secure multi-party
806 computation (Goldreich, 1998) or emerging solutions based on
807 homomorphic encryption (Gentry and Boneh, 2009).

808 Individual Control vs. Organizational 809 Control of Personal Data

810 Except for the case where the biometric template is stored locally
811 on the user's device (mostly for verification purposes), in all other
812 cases described above, the biometric and personal identifying
813 information is not under the possession of the data subject, but
814 rather that of the organizations that collect, store and administer
815 the data for a particular identity system. While data protection
816 regulations—especially in Europe—enable the data subjects to
817 restrict the collection and processing of personal data (Tikkinen-
818 Piri et al., 2018), once collected, such data might remain under
819 the control of whoever owns the hardware (servers, devices)
820 where the data is stored. The same is true for behavioral and
821 social data that corporations collect about their users, which are
822 statistically compiled as identity profiles that may be used for
823 purposes of advertisements, alternative credit scoring, identity
824 verification, and so on (Bygrave, 2012).

825 Privacy laws and data protection regulations provide some
826 protection in terms of how information may be stored, used or
827 collected. However, data protection regulations merely impose an
828 obligation for data collectors and processors to obtain *informed*
829 *and explicit consent* from the data subjects before they can
830 engage in the collection or use of personal data for a particular
831 purpose (Kosta, 2013). Some jurisdictions—such as Europe
832 with the newly enacted General Data Protection Regulation¹⁸—
833 have introduced additional rights, including the right to data
834 portability¹⁹ and the right to erasure²⁰ (better known as the
835 right to be forgotten). Yet, where such protections do not
836 exist, there is a risk that personal data (including biometric
837 templates or samples) will remain siloed by the organizations
838 that control them, with no real possibility for the data subject to
839 request the deletion or the portability of such data—unless such
840 organizations implement their own privacy policies that enforce
841 these requirements.

842
843
844 ¹⁸The General Data Protection Regulation (GDPR) 2016/679 is a regulation in EU
845 law on data protection and privacy for all individuals within the European Union
846 and the European Economic Area.

847 ¹⁹Article 20 of the GDPR stipulates that: “The data subject shall have the right to
848 receive the personal data concerning him or her, which he or she has provided to a
849 controller, in a structured, commonly used and machine-readable format and have
850 the right to transmit those data to another controller without hindrance from the
851 controller to which the personal data have been provided”

852 ²⁰Article 17 of the GDPR stipulates that: “The data subject shall have the right
853 to obtain from the controller the erasure of personal data concerning him or her
854 without undue delay and the controller shall have the obligation to erase personal
855 data without undue delay where one of the following grounds applies: the personal
856 data are no longer necessary in relation to the purposes for which they were
857 collected or otherwise processed.”

856 Biometrics vs. Other Types of Identifiers

857 While biometrics provide interesting benefits to an identity
858 management system, they are not devoid of any drawback. First
859 of all, using biometric data to create a singular and unique
860 identifier obliges individuals to identify themselves as one and
861 only one person—even when it is not necessary for a particular
862 use case (Jain et al., 2004)—which may present significant privacy
863 issues, especially in the case of political refugees.

864 Biometrics can also be significantly more problematic than
865 traditional forms of authentication (e.g., passwords and other
866 identifiers such PIN codes, hardware devices, etc.) because one
867 cannot change his or her biometric data (Prabhakar et al.,
868 2003). Importantly, biological information is effectively public
869 information: we are leaving biological information everywhere,
870 e.g., fingerprints, DNA, recordings of our gait, photographs of
871 our faces or irises—from which advanced computer algorithms
872 can extract a biometric template (Mordini and Massari, 2008).
873 Fingerprints are easily stolen, copied, or lifted. Facial recognition
874 can be easily spoofed through photographs or videos. Iris scans
875 or behavioral biometrics such as gait may be more difficult
876 or expensive to spoof or copy, but are not foolproof (e.g.,
877 contact lenses can fool iris scans). Accordingly, because of their
878 inherently public nature, biometrics should only be used as the
879 username (i.e., public key) rather than the password (i.e., private
880 key). Whenever biometrics are used, some form of second factor
881 authentication should be required, such as a PIN or a physical
882 token, verification of photo ID or a physically present person
883 (Rane et al., 2013).

884 Moreover, our bodies are subject to physical change. Iris scans
885 become clouded due to cataracts. Fingerprints may disappear due
886 to hard labor or burns. Gait may change due to aging, accidents,
887 or illness. According to a study²¹ by the National Institute of
888 Standards and Technology (NIST), even in healthy people, the
889 error rate for single iris scans can range from 2.5% to up to
890 20% in some cases—a significant percentage given the world's
891 population of 7.5 billion people. As identity practitioners like
892 Vinay Gupta have argued, because of the complex variation and
893 nuance of biological forms, it is fundamentally impossible to
894 rely on biometric measures as singular and unique identifiers
895 for human beings²². Indeed, if biometrics are used as a universal
896 identifier of one's identity and rights, the consequences for those
897 in the three percent baseline error rate may be paralyzing and
898 dire. For instance, in the case of India's biometric ID system, one
899 study showed that 20 percent of the households in Jharkand state
900 had failed to get their food rations due to biometrics errors—
901 which is five times higher than the failure rate of ordinary
902 ration cards²³.

903 Finally, because of the public perception of biometrics as being
904 more “scientific” and therefore more authoritative, the downside
905 errors of biometrics is often overlooked. Yet, if a biometric
906 identifier is used as the backbone of an identity management
907

908 ²¹https://www.nist.gov/publication/get_pdf.cfm?pub_id=910385

909 ²²<https://medium.com/humanizing-the-singularity/a-blockchain-solution-for-identity-51fbcae94caa>

910 ²³<https://www.independent.co.uk/news/world/asia/india-tech-fingerprint-eye-scan-id-food-benefits-bank-accounts-a8297391.html>

913 system used for the protection of fundamental rights and
 914 privileges, it cannot fail disastrously, even if the probability of
 915 a failure is very small. Ideally, a properly functioning identity
 916 system must be resilient against low probability but highly
 917 consequential negative events and gains value from increased
 918 input and interactions with the world. However, an identity
 919 system that relies on biometrics as the only authoritative
 920 identifier is not only a brittle and fragile system (Friedman et al.,
 921 2011), it is also highly problematic from a cybersecurity and
 922 privacy perspective (Prabhakar et al., 2003; Campisi, 2013)—
 923 which is particularly relevant for vulnerable populations such as
 924 migrants and refugees.

925 926 927 **SELF-SOVEREIGN IDENTITY AND** 928 **CREDENTIAL MANAGEMENT SYSTEMS** 929

930 The notion of self-sovereign identity has emerged in the past few
 931 years, although there is no agreed upon definition yet on what
 932 the terminology really means (van Wingerde, 2017). On a general
 933 level, self-sovereign identity is intended to preserve the right
 934 for the selective disclosure of different aspects of one's identity
 935 and the various components thereof, in different domains
 936 and contextual settings. This right should apply irrespectively
 937 of whether these aspects and components have been issued
 938 by a particular government, company, or organization. More
 939 specifically, self-sovereign identity also refers to the idea that
 940 individuals shall retain control over their personal data and,
 941 to a certain degree, over the representations of their identities
 942 (or personas) within a particular identity management system.
 943 This requires giving them the ability to establish (and control)
 944 who has the right to access specific pieces of information
 945 about them, with a high degree of granularity (Der et al.,
 946 2017).

947 From a technical perspective, self-sovereign identity is
 948 generally regarded as a new paradigm of online identity
 949 management, whereby individuals and entities can manage
 950 their identity-related information (i.e., identifiers, attributes
 951 and credentials, or other personal data) by storing them
 952 locally on their own devices (or remotely on a distributed
 953 network) and selectively grant access to this information to
 954 authorized third parties, without the need to refer to any trusted
 955 authority or intermediary operator to provide or validate these
 956 claims (Mühle et al., 2018). This enables greater control over
 957 personal identifying information, or other relevant data about
 958 an individual or entity. Because digital identifiers can be in
 959 a variety of formats, an important requirement for a global
 960 identity system is the establishment of technical standards for
 961 interoperability. We describe below the most prevalent standard,
 962 the Decentralized Identifier (DID), that we mentioned earlier in
 963 the paper.

964 965 **Open Source Digital Identity and Verifiable** 966 **Claims Web Standards** 967

968 The World Wide Web Consortium (W3C) is a technical
 969 standards body for the open internet, working on a decentralized

970 identifier (DID) standard²⁴ DIDs are a new type of identifier
 971 for verifiable, self-sovereign digital identity that is universally
 972 discoverable and interoperable across a range of systems²⁵
 973 The DID standard is supported by the Decentralized Identity
 974 Foundation, a consortium of companies that are developing
 975 and building applications using the DID standard, including
 976 Microsoft, IBM, Hyperledger, Accenture, Mastercard, RSA, and
 977 all the major blockchain identity and data companies such as
 978 Civic, uPort, BigChainDB, Sovrin, and many others²⁶.

979 DIDs are URLs (i.e., unique web addresses) that resolve to
 980 a DID Document, which provides information on how to use
 981 that specific DID²⁷. For example, a DID Document can specify
 982 that a particular verification method (such as a cryptographic
 983 public key or pseudonymous biometric protocol) can be used
 984 for the purpose of authentication. The DID document might
 985 also reference a series of service endpoints, enabling further
 986 interactions with the DID controller. For instance, a DID can
 987 reference the location of associated personal data, which a
 988 requester would need to ask the DID controller for permission
 989 to access (McMullen et al., 2019).

990 A DID by itself is only useful for the purpose of authentication.
 991 It becomes particularly useful when used in combination with
 992 verifiable claims or credentials—another W3C standard that
 993 can be used to make any number of attestations about a DID
 994 subject (Dunphy and Petitcolas, 2018). These attestations include
 995 credentials and certifications that grant the DID subject access
 996 rights or privileges. For example, a verifiable claim can attest that
 997 an individual has been Know-Your-Customer (KYC) approved
 998 and therefore eligible to open a bank account, that the same
 999 individual has been certified as eligible to drive, or authorized
 1000 to access certain programs as a system administrator (Aydar and
 1001 Ayvaz, 2019).

1002 A verifiable claim contains the DID of its subject (e.g., a bank
 1003 customer), the attestation (e.g., KYC approval), and must be
 1004 signed by the person or entity making the claim using the private
 1005 keys associated with the claim issuer's DID (e.g., the bank).
 1006 Verifiable claims are thus methods for trusted authorities, such
 1007 as banks, to provably issue a certified credential associated to a
 1008 particular DID. DID claims remain under the control of the DID
 1009 subject and can be used to prove a particular attribute of the DID
 1010 subject, independently from a certificate authority, an identity
 1011 provider or a centralized registry (Baars, 2016). Proving to be
 1012 the actual subject of that DID (through a specified authentication
 1013 method) will enable an individual or entity to benefit from access
 1014 privileges associated with these credentials.

1015 While DIDs are independent of and do not require blockchain
 1016 technology, they are designed to be compatible with any
 1017 distributed ledger or blockchain network. Since a DID may be
 1018 associated with a particular private/public key pair used to sign
 1019

1020 ²⁴W3C is led by internet industry pioneer Tim Berners-Lee, who invented the
 1021 World Wide Web. W3C has 479 members including all the major internet
 1022 and technology companies such as Amazon, Apple, Boeing, Cisco, Microsoft,
 1023 Google, Facebook, Alibaba, Tencent, Baidu, along with research universities and
 1024 governments. See <https://www.w3.org/>

1025 ²⁵See W3C DID primer for introduction: <https://github.com/w3c-ccg/did-primer>

1026 ²⁶<https://identity.foundation/>

1027 ²⁷<https://w3c-ccg.github.io/did-spec/>

identity claims, it is possible to associate that key pair (i.e., the key pair linked to the DID) with key pairs used to sign financial transactions on a blockchain. Most importantly, the DID specification also makes it possible to associate particular methods to a DID, which specifies the procedures for key registration, replacement, rotation, recovery, and expiration. Several method schemes have been implemented so far that leverage the resilience and tamper-resistance of blockchain technology to manage DIDs (e.g., BTCR DID, Blockstack DID, Ethereum ERC725 DID)²⁸. The W3C group is working to ensure technical interoperability between different DID methods.

It is important to note, however, that given the transparency and immutability of a blockchain, personal information should never be stored on the blockchain itself (De Filippi, 2016). Yet, a blockchain can be used to track permissioning and access of personally identifying data that is stored off-chain, thereby creating an auditable trail of information access. Therefore, in addition to the standardized DID methods, a blockchain can also be used for the recording and eventual revocation of claims or attestations, for the granting and revocation of access to personal data stores²⁹, and other functions that may be specific to particular identity system (e.g., claims filed and resolved as part of a dispute resolution system regarding false attestations).

A Road-Map Toward Self-Sovereign Identity

The road toward true self-sovereign identity is still long, as we are only at the early stages of understanding how to implement a digital identity system that provides full control and autonomy to the individuals. Yet, in light of the refugee crisis in Europe, and the increasing number of displaced people who lack a formalized form of identification, today—perhaps more than ever—the quest toward self-sovereign identity has become of crucial importance.

As described earlier, self-sovereign identity solutions are designed to give individuals control over their own identity—that is, people should have the possibility to decide precisely what information to disclose about themselves, to whom, and under what circumstances. Under a self-sovereign identity model, identity providers should not have the possibility to prevent individuals from exercising basic human rights, such as the right to be oneself, the right to freedom of expression and the right to privacy. While this does not necessarily require individuals to be the sole holders of any information regarding themselves, an important precondition for self-sovereign identity is that digital identities are not locked into any given platform, nor controlled by a given operator, but rather remain portable and interoperable across multiple platforms, so that individuals are free to choose the identity operator that they trust the most, and to move from one operator to another, if so desired.

While a precise definition of what constitutes a self-sovereign identity does not currently exist, a series of criteria have been identified as the underpinning principles of self-sovereign

identity³⁰. These principles can be regarded as a preliminary benchmark to assess existing self-sovereign identity solutions:

1. **Existence:** individuals must have an independent existence, independently of the digital identifiers that merely serve as a reference to them.
2. **Control:** individuals must control their identities, they should always be able to refer to it, update it, or even hide it—even if others can make claims about these identities.
3. **Access:** individuals must have access to all the data related to their identities, and should be able to retrieve them claims whenever needed.
4. **Transparency:** systems and algorithms used to administer and operate digital identities must be open and transparent, with regard to both their operations and maintenance.
5. **Persistence:** identities must be long-lived, preferably they should last forever, or at least for as long as the user wishes to maintain them.
6. **Portability:** information and services about identity must be transportable, and not be held by a single third-party entity, even if it's a trusted entity.
7. **Interoperability:** identities should be as widely usable as possible, as opposed to being framed only to work in siloed environments.
8. **Consent:** individuals must agree to the use of their identities, sharing user data must only occur with the consent of the data subject.
9. **Minimization:** disclosure of claims must be limited to the minimum necessary to accomplish the task at hand
10. **Protection:** the rights of users must be protected at any cost, even if doing so would go counter to the interests of the identity providers.

Most digital identity projects will not meet all of these criteria—and many do not even purport to qualify as “self-sovereign” identity projects—we will discuss in this paper two case studies that make use of biometrics in combination with blockchain technology to provide users with a certain degree of sovereignty over their digital identities. The first case study is the *Kiva Protocol*, which focuses on identity for credit scoring and secure sharing of credit history amongst microfinance institutions. The second case study is the World Food Programme's *Building Blocks* and its biometric identity solution for delivering services to beneficiaries in need—particularly in providing better delivery of services to beneficiaries served by multiple UN agencies.

These two initiatives were chosen because of their higher degree of technological readiness with respect to other alternatives, their credibility and their potential impact in terms of future large-scale deployment, and, finally, because of the previous experimentations they have undertaken, which enabled us to collect valuable data points concerning the extent to which their current implementation fulfills the criteria of a self-sovereign identity system.

²⁸A list of currently available DID method schemes is available at: <https://w3c-ccg.github.io/did-method-registry/>

²⁹For a general overview of the different blockchain-based self-sovereign identity solutions and their characteristics, see (McMullen et al., 2019).

³⁰The Path to Self-Sovereign Identity, written by Chris Allen and the Rebooting Web of Trust community: <https://github.com/WebOfTrustInfo/self-sovereign-identity/blob/master/ThePathToSelf-SovereignIdentity.md>

As the following sections describe, these two projects have prioritized specific principles of self-sovereign identity that are most relevant to their use cases. In both of the cases, it appears that the identity solutions focus, first and foremost, on principles relating to interoperability and the secure sharing of identity claims between parties. The principles of minimization, consent, portability, and persistence are also given significant importance. The use of a blockchain ledger is useful because it enables data to be shared securely across multiple parties, and parties must be granted permission in order to access and append information to the blockchain. From an identity perspective, a persistent and portable digital identity and digital history is highly valuable to vulnerable populations who are often on the move. The validity of the attestations, especially from trusted organizations such as Kiva and UN agencies, are important for the identity subject to establish or re-establish credibility and access to resources.

However, the principles of control and access remain difficult to achieve from a technical perspective in developing economies, as smartphone penetration and technical knowledge necessary for self-custody is still nascent. The lack of proper connectivity and hardware infrastructure (e.g., while most refugees do have a mobile phone, they do not always have a smartphone) is a key obstacle to overcome in the roadmap toward self-sovereign identity. Both Kiva and the Building Block initiatives therefore had to implement custodial models for their identity solutions, significantly reducing the degree of control that individuals can exercise over their digital identities. However, that may change over time as smartphones become cheaper and users become more technically knowledgeable. In any event, both case studies provides valuable lessons concerning the multiple obstacles associated with the implementation of self-sovereign identity solutions in the humanitarian context, and the different approaches adopted by each of these initiatives, as an attempt to overcome these obstacles in the short term while focusing on the immediate user needs.

KIVA CASE STUDY: SOLVING FOR CREDIT HISTORY³¹

Kiva³² is building an identity protocol that is expected to be rolled out across the whole country of Sierra Leone—this is a testament to the strength of the programme and the significance of provisioning vulnerable persons with a digital identity system.

Kiva is based on the DID and credentials model described above, using Hyperledger Indy as the underlying blockchain layer. It relies on a credential-based identity system, whose basic identifier is a public/private key pair, to which multiple claims and attestations can be associated. In the Kiva protocol, issuers of verifiable credentials are called “trust anchors” who have real world reputations at stake. The Kiva identity protocol is currently designed as a private permissioned system, whereby all trust anchors must be approved by Kiva and/or the Sierra Leone government in order to issue credentials, sign attestations,

³¹Most of the information in this section has been drafted as a result of several calls and interviews with Kevin O'Brien and Aaron Goldsmid from Kiva.

³²<https://www.kiva.org/protocol>

and read identity claims. In the future, trust anchors may be broadened to include NGOs, technology companies such as Facebook and Google, and other organizations that can provide information relevant to a particular identity³³.

Currently, trust anchors are limited to the Sierra Leone government bodies and microfinance institutions, because of the immediate goal of solving the problem facing the microlending industry—whereby many constituents are ineligible for loans due to lack of any formal identity and history (data for underwriting loans). In fact, the government of Sierra Leone, through the influence of the Central Bank which issues bank licenses, will *require* that all microfinance institutions, banks and other financial institutions, participate as credential issuers for Kiva's identity system. This is particularly relevant for microlending in developing economies that do not have national credit bureaus, making it difficult for lenders to check cross indebtedness. Without the ability to check the total indebtedness of a borrower, it is difficult to properly price default risk and underwrite these loans.

The Kiva protocol functions like a credit bureau with greater privacy and control by the individual compared to traditional credit bureaus. The credit profile, comprised of linked credit attestations and claims, is portable by the individual, rather than locked within a centralized credit bureau. Importantly, individuals have control over who can access their profiles, whereas currently anyone can perform a credit check without permission. Under the Kiva model, an individual may decide whether to provide a lender access to her credit history.

Kiva will provide every Sierra Leone citizen eligible for a government issued ID with a DID and associated public/private key pair to sign identity claims, along with a first attestation from the Sierra Leone government (in the form of a verifiable credential containing hashes of the citizen's biometrics and other government-issued identifiers). In the Kiva framework, biometrics are simply another attribute that is attached to the DID, similar to a date of birth, place of birth, or any other piece of identity information. This reduces much of the systemic risk of using biometrics as an exclusive form of identification, as described above. In this system, because biometric data do not serve as an identifier, biometrics will be used primarily for verification rather than for identification purposes.

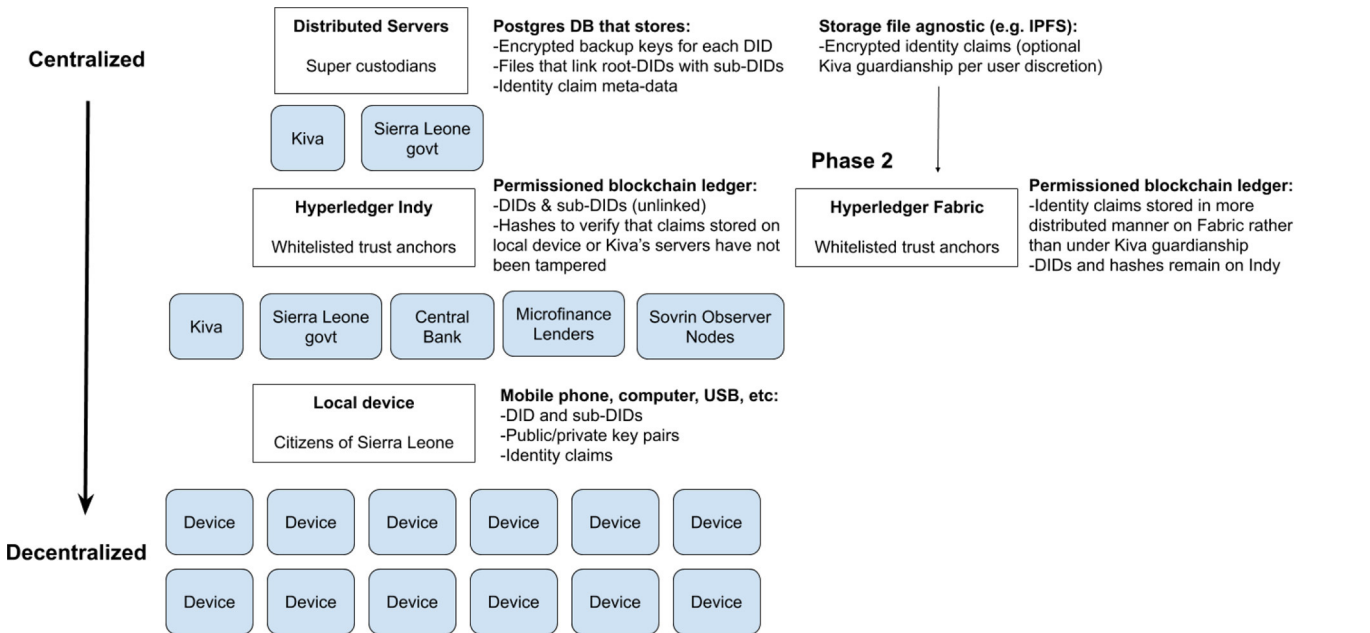
Anyone seeking to access the information linked to that profile must request the DID subject (i.e., the Sierra Leone citizen) to grant permission. The Hyperledger blockchain is used to record that a third party (as identified by its public key linked to a DID) requested, was granted, and was eventually revoked access to the relevant verifiable claims or credentials, according to timestamps. Each citizen will have a root-DID that maps to an unlimited number of sub-DIDs that are generated for each new loan transaction or relationship with a lender. Sub-DIDs can also

³³A future identity protocol may enable permissionless trust anchors that do not need to be centrally approved *ex ante*; or else, trust anchors may be automatically approved according to a set of programmable rules e.g., number of credentials or types of credentials associated with a particular trust anchor to establish their reputation.

be created for different purposes i.e., each sub-DID represents a different persona or profile. The use of sub-DIDs enables a degree of privacy (see below section on privacy).

Kiva Protocol Architecture

The following is a high-level architecture of the Kiva identity protocol:



In an ideal model, all sensitive information, such as private keys, the files that link root-DIDs with sub-DIDs, identity claims and other information are stored only locally on devices controlled by the identity subject, such as mobile phones and computers. Thus, control and storage of personal information is structurally decentralized. In developing countries, however, this will take time as smartphone penetration is still low (though growing rapidly in many markets) and many people may not necessarily own individual devices i.e., a phone may be shared amongst a family. Currently, it is not possible to securely store private keys on feature phones. Therefore, it is likely that third parties such as non-profits or commercial businesses may serve as proxies that help manage private keys or shared devices. Ideally, private keys are never shared and remained locked in wallets on shared devices, whereby users can unlock their individual private keys using biometrics, PIN or password when they access the shared device.

Even if non-profits and other community organizations serve as trustees or proxies to help users manage their private keys, backups of identity claims and private keys will be necessary. In light of the practical difficulties of managing the public/private key pairs associated with a particular DID, the Kiva identity protocol deploys a guardianship model, whereby Kiva and the Sierra Leone government serve as the super custodians in the system. Kiva will escrow the key pairs on behalf of the identity subject, who may take the key pairs out of escrow at any time. Under Kiva's guardianship model, backup keys in custody

are encrypted and can only be restored through a multi-factor process e.g., biometrics and/or PIN.

Kiva's servers also store the data files that map the links between root-DIDs and related sub-DID, as well as backup copies of encrypted identity claims (with accompanying meta-data) on a separate data storage format such as IPFS. In the next phase of the protocol, the encrypted identity claims may be stored

in a more distributed manner on a permissioned ledger such as Hyperledger Fabric, which is better designed to store data, whereas Hyperledger Indy is fit-for-purpose for validating DIDs.

The most private and sensitive data is held in guardianship on Kiva's distributed servers in a Postgres database. A local copy of the database (or parallel database) may be maintained by the Sierra Leone government, pursuant to Sierra Leone data localization regulations that require sensitive citizen data to be stored in-country.

Beneath the Kiva guardianship layer is the private permissioned blockchain ledger running on Hyperledger Indy. The Central Bank of Sierra Leone would be a permissioned node, along with Kiva and the Sierra Leone government. Because the Central Bank is requiring all lending institutions to report loan transactions on the protocol, the microfinance lenders and other financial institutions that fall under the Central Bank's mandate will be required to register as nodes. In addition, other parties such as non-profits, may apply to be Trust Anchors or Stewards (Sovrin observer nodes), which helps increase the security and resiliency of the ledger by diversifying nodes away from entities domiciled in Sierra Leone.

The nodes store copies of the unlinked DID and sub-DIDs, as well as hashes of the associated identity claims. As noted above, Hyperledger Indy is not designed to store actual claims data, which identity subjects will have the choice to store in Kiva's guardianship, and later those claims can be migrated to

1369 Hyperledger Fabric, which is built to support claims data, as
1370 described above.

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1372 **Interacting With the Kiva Protocol:** 1373 **Step-by-Step**

1374 We describe here the intended step-by-step operations of the
1375 Kiva protocol, and how a Sierra Leone citizen might interact
1376 with the Kiva protocol, once fully deployed. The Sierra Leone
1377 government will deploy campaigns to enroll citizens into the
1378 identity protocol. Citizens will register at polling stations, where
1379 they will receive both a physical ID card with biometrics and
1380 a digital ID, in the form of a DID and associated private keys
1381 held in a wallet, ideally on the individual's device. In many
1382 cases, as described above, the individual may not own a phone
1383 or have a phone with the capability to hold private keys in
1384 a wallet. In this case, the keys and future identity claims will
1385 be held in guardianship by Kiva. The government of Sierra
1386 Leone will make the first attestation by signing an identity claim
1387 that the individual is a citizen of Sierra Leone with official
1388 identity information such as biometric string, date of birth and
1389 other data.

1390 When the individual, whom we will call Mary, goes to the
1391 local microfinance lender to ask for a loan, the bank will
1392 first ask for Mary's identity claim signed by the government
1393 of Sierra Leone (the official state ID). Mary will access an
1394 application (either on her phone or on a device at the bank)
1395 that grants the bank permission to validate the government's
1396 signed claim. Ideally, to preserve privacy, a bank does not
1397 actually read the contents of the claim (e.g., the biometric,
1398 the date of birth) if such information is not actually relevant
1399 for purposes of KYC or credit underwriting. All the bank
1400 needs to know is that the government has signed a valid claim
1401 attesting to Mary's identity, which fulfills the bank's minimum
1402 KYC obligations.

1403 Next, the bank will ask Mary for permission to disclose
1404 her credit history. If Mary says yes, Mary will then unlock
1405 her identity claims using her private key. The bank will then
1406 validate the identity claims against the hashes in Hyperledger
1407 Indy to confirm that the identity claims are both complete
1408 and authentic. If there is an error, the bank will receive a
1409 failure message.

1410 If Mary is unable to use her own device to manage identity
1411 claims and keys, the bank will ask for permission to retrieve the
1412 identity claims from Kiva's servers directly. In order to sign this
1413 permission using her keys in Kiva's custody, Mary would need
1414 to provide a second factor authentication such as her biometrics
1415 or PIN.

1416 Once a loan is approved, the bank would sign identity
1417 claims relating to the loan disbursement and repayment.
1418 Mary would receive messages to her mobile phone application
1419 informing her that the bank is writing a claim e.g., regarding
1420 repayment, and Mary could accept this action³⁴. The claim
1421 would be sent to Mary's device, if she chooses to only
1422

1423 ³⁴Initially, Mary will give permission at the outset for her bank to write *all* claims
1424 related to her loan for the duration the loan remains outstanding. In the future,
1425 Kiva hopes to provide even greater control to users (especially as technology

1426 keep data on her local device; or else the claim would
1427 be encrypted and stored in Mary's wallet in guardianship
1428 on Kiva's servers (Kiva may also store a backup copy if
1429 Mary so chooses even if she manages her data on her
1430 own device).

1431 Mary may also initiate a dispute resolution action if she
1432 believes the bank has written an incorrect claim or failed
1433 to provide a claim for a repayment. The dispute resolution
1434 process will likely be off-chain, whereby Mary would file a
1435 ticket with the facts to be decided by an arbitral body. If
1436 the arbitral body decided in Mary's favor that she did indeed
1437 pay the bank in cash for her monthly installment, the arbitral
1438 body would then require the bank to sign such a claim,
1439 or else the arbitral body could sign such a claim with its
1440 own keys.

1441 Where loans are made and repaid in cash, Mary would need
1442 to trust her bank to make the repayment claim. She would likely
1443 receive a physical receipt for her cash repayment, which she
1444 could present to the bank to request a repayment claim (or
1445 to an arbitrator if her bank fails to do so). In a future model,
1446 if the loans were disbursed as digital currency, disbursements,
1447 and repayments could be automatically recorded as identity
1448 claims, with the blockchain transactions appended as proof
1449 of payment.

1450 **Privacy Considerations vs. the Problem of** 1451 **Selective Disclosure**

1452 In order to maintain privacy and reduce fallout from security
1453 breaches, the Kiva protocol strives to operate under the
1454 principles of zero knowledge proofs, whereby only the absolute
1455 necessary information is exposed and measures are taken
1456 to ensure that no one can seek information in the system
1457 without permission. Accordingly, each loan that Mary takes
1458 will be associated with a new sub-DID, rather than directly
1459 tied to her root-DID. This prevents banks from being able
1460 to monitor future credit activity tied to a root-DID without
1461 asking the identity subject for permission, as future credit
1462 transactions will be associated with newly generated sub-DIDs,
1463 and banks do not have access to the file that maps sub-DIDs to
1464 the root-DID.

1465 Privacy is countered with the problem of selective disclosure,
1466 whereby lenders must check for cross-leverage. During the
1467 underwriting process, Mary's bank can see the full credit history
1468 across her sub-DIDs because during the validation process,
1469 the bank will first query Kiva's servers to get the universe of
1470 sub-DIDs tied to Mary's root-DID. As described above, the
1471 file that maps sub-DIDs to a root-DID is only available on
1472 Kiva's servers. However, at no time is the bank exposed to
1473 the actual sub-DIDs or root-DID; the bank is only exposed
1474 to the transaction claims associated with the sub-DIDs. The
1475 bank will then proceed to match the transaction claims against
1476 the hashes in Hyperledger Indy to authenticate the claims, as
1477 described above.

1480 penetration improves), such that Mary would be able to grant permission for *each*
1481 claim that the bank wishes to append to her profile.
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Mary grants Bank permission to query her credit history

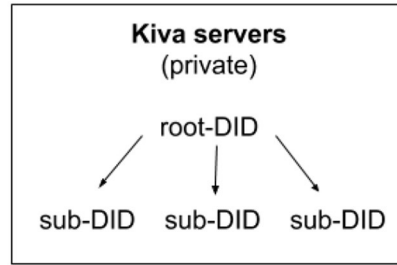


Bank grants Mary a loan

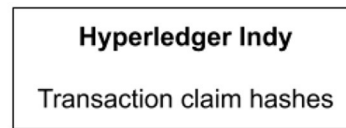


Bank queries universe of relevant sub-DIDs

Hashes validate authenticity of claims



Bank is exposed to only relevant transaction claims



Even in the case of a fully self-sovereign identity system, not all data will be owned and controlled by the individual, as some of the data may be produced and maintained by third parties making attestations. For example, a bank will retain control over its own records regarding an individual's lending history with that bank. However, compared to a centralized credit bureau, information will not be centrally aggregated and communicated to a single operator. Data can remain stored by third parties, while the associated attestation (in the form of a verifiable claim) is assigned and controlled by the individual and stored on the blockchain. Hence, even though the citizens of Sierra Leone may not control all the information regarding them, they nonetheless control the set of verifiable credentials that represent their attributes, which they can freely combine into a useful identity or set of profiles and personas.

Finally, it is important to note that Kiva's identity system is, at its root, a repository of verifiable claims data, which does not discriminate against politically sensitive identity claims. While it has been designed for Sierra Leone, the same identity system may be applied, for example, to Syrian refugees, allowing the Syrian government to issue attestations concerning the identity of a particular refugee, with a signature and time stamp. If the Syrian government that issued the identity no longer exists, the refugee will nonetheless be able to prove his or her identity at that particular point in time.

In returning to our list of self-sovereign identity principles, the Kiva identity system focuses first on consent, interoperability, and minimization. This serves the primary use case of enabling microfinance institutions to share information and create a persistent record of credit history, in a way that still preserves the privacy of the borrower by revealing only the necessary information for a microfinance institution to make a decision. While most users will not be self-custodying their identity information from the outset due to technical challenges, the system is designed such that users may opt out of Kiva serving

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as a super custodian. Over time, self-custody and control will become more prevalent, and identities remain globally portable and persistent.

WORLD FOOD PROGRAMME CASE STUDY: SOLVING FOR OPTIMIZATION AND HARMONIZATION OF AID ACROSS U.N. AGENCIES³⁵

Background

The World Food Programme (WFP)³⁶ is the food assistance branch of the United Nations and the world's largest humanitarian organization addressing hunger and promoting food security. WFP provides food assistance to more than 80 million people in more than 80 countries.

In the past several years, the trend has been to enable the people served to make their own purchasing decisions through Cash-Based Interventions (CBI) rather than in-kind food distributions. In 2018, WFP distributed more than USD 1.7 billion in CBI, more than half of the global cash aid distributions³⁷. In the right conditions, CBI programs can be more cost-effective and beneficial to the local economies as well as providing an increased element of dignity to the people served.

WFP has pioneered innovation amongst UN agencies, recognizing the potential for blockchain technology in CBI as fourfold: (1) improved efficiencies such as reductions in costs and risks and enhancements in accountability and control, (2) creating a unified view of the people served thereby reducing duplication and fragmentation, creating

³⁵MOST OF THE INFORMATION IN THIS SECTION HAS BEEN DRAFTED AS A RESULT OF SEVERAL CALLS AND INTERVIEWS WITH HOUMAN HADDAD FROM THE WORLD FOOD PROGRAMME.

³⁶<https://www1.wfp.org/overview>

³⁷<https://www.economist.com/free-exchange/2014/03/03/giving-generously>

opportunities for optimization and harmonization, and linking various aid actors through a single connection to the blockchain, (3) multiplying the redemption options (such as ATMs, food stores, health networks, and schools) available to the participating organizations and the people served, and (4) paving the way for blockchain based digital identities by demonstrating the underlying technology in practice and bringing key stakeholders together around a neutral blockchain network.

Building Blocks

In this section, we describe WFP's blockchain-based CBI project called "Building Blocks"³⁸ Building Blocks was born in January 2017 with a 100-person Proof-of-Concept (PoC) in Pakistan's Umerkot village. At the time, the aim was to demonstrate that blockchain can be used beyond the cryptocurrency application.

For the PoC, beneficiary accounts were created on the blockchain and loaded with tokens representing cash or food and each beneficiary was assigned a random identifier between 1 and 100, which was linked to their public key one-to-one. To redeem their entitlements, beneficiaries would present themselves at cash or food merchants and provide their random identifier. The merchant would then insert the beneficiary's identifier along with the redemption amount into a web application. The web application would send the request to Building Blocks which would then send a One-Time Password (OTP) to the beneficiary's feature phone via SMS as the authentication mechanism. The beneficiary would then provide the OTP to the merchant who would insert it into the web application and send it to Building Blocks. If the OTP was valid, Building Blocks would check the requested redemption amount against the available blockchain entitlements and, if sufficient, trigger the beneficiary private key held in custody to record a transaction and send a confirmation back to the merchant. Upon seeing the confirmation, the merchant would distribute the requested quantity of cash or food to the beneficiary. WFP would then, based on the Building Blocks record, determine the amount owed to each merchant and settle with them directly.

For the PoC, Building Blocks used the public Ethereum blockchain. This decision was based on the fact that public chains are self-sustaining through crypto-economic incentives and a public network of validators, and therefore not dependent on WFP or the UN. However, the project team observed that major public chains have low transaction throughput and expensive transaction costs due to the prevalence of the Proof-of-Work (PoW) consensus mechanism, which is based on computational power in order to secure transactions to the public ledger.

Jordan Implementation

Having demonstrated the concept of using a blockchain ledger, and incorporating the learnings from the PoC, in May 2017 Building Blocks initiated a large-scale pilot with 10,000 Syrian refugees in Jordan. The concept was similar to the Pakistan PoC. However, for the Jordan pilot, Building

Blocks switched to a private, permissioned blockchain using the Parity Ethereum client with a Proof-of-Authority (PoA) consensus algorithm.

The private PoA network provides Building Blocks with a very high transaction throughput at no cost per transaction. The private network also provides higher assurances for data protection privacy. The main downside of the private network is that it is not self-sustaining. However, the smart contract code is identical between private and public networks. Therefore, when the public networks have adequately addressed the throughput, cost, and privacy issues, Building Blocks can switch by merely copy-pasting its code. Another downside is that a private network is less resilient and tamperproof than public networks due to the fewer nodes. However, with each additional independent node on the blockchain, a private chain becomes increasingly closer to the characteristics of public chains in terms of resilience and immutability.

In contrast to the Pakistan PoC whereby authentication was provided through OTP SMS, in Jordan Building Blocks integrated with the existing iris biometric authentication system enabled by the UN Refugee Agency (UNHCR)³⁹. Through Building Blocks, refugees only need to scan their irises at the point-of-sale to receive food assistance. All transactions are recorded on a private blockchain-based infrastructure, used as a registry to calculate the balance of every refugee, as well as the amount of funds that must be disbursed by the WFP to the relevant merchants⁴⁰. The advantage of this system is that beneficiaries can access and transfer funds by merely presenting themselves in front of the biometric-based identification system, without the need for a device such as a mobile phone. Indeed, given the precarious situations of Jordan refugees, it is not possible to assume constant internet connectivity or that beneficiaries will always own sufficiently sophisticated phones to handle key management. Facilitating seamless access to critical resources such as food or funds is particularly important for refugees in critical need.

Like Kiva, WFP faces issues with end user smartphone ownership and data connectivity. Hence, Building Blocks also has a guardianship model for custody of keys used to sign transactions. WFP functions as a custodian of the beneficiaries' private keys, which, through the biometric iris authentication, are triggered to sign blockchain transactions related to CBI. Like the Kiva model, the WFP model is also designed to enable self-custody should a user elects to do so when sufficient infrastructure is in place to make this feasible e.g., availability of affordable smartphones with key management capabilities. Eventually, the aim is to provide all the beneficiaries with a new set of public-private key pairs (which they will create and have full control over) and transfer their aid credits to these new wallets.

³⁹<https://www.unhcr.org/en-us/>

⁴⁰<https://www.technologyreview.com/s/610806/inside-the-jordan-refugee-camp-that-runs-on-blockchain/>

As noted earlier, WFP's Building Blocks uses the UNHCR's Biometric Identity Management System (BIMS)⁴¹ for authentication. Biometric data in BIMS may include original digital scans (such as the iris photographs), feature sets (i.e., biometric template abstracted from the digital scans), and the reduction of feature sets into a data string that functions as a unique identifier. During the registration process, UNHCR collects an individual's biometrics and associates the biometric data (reduced to a data string) with a unique random identifier in the BIMS database. Individuals are then grouped into family units (as a second level abstraction), each with their unique identifier (a 12 characters string).

Authentication in the context of the UNHCR cash aid system requires a beneficiary to provide an iris scan at the point of sale (POS) for every transaction. The process operates as follows: first, the biometric system at the POS is used to collect the biometric data through an iris scan. The scan is then converted to a template and communicated to the UNHCR and matched against the universe of templates in the BIMS database to retrieve the unique identifier associated with the beneficiary's family unit. This identifier is then sent to the WFP's Building Block system to retrieve the public-private key pairs associated with that identifier. The public key will be used to check if the beneficiary's balance is sufficient to make the transaction. If the balance is sufficient to cover the transaction, the private key will be triggered to sign the transactions on the blockchain, on behalf of the beneficiary. Each communication leg in the entire process is end-to-end encrypted.

For the time being, the system has implemented a series of best practices to mitigate the risk of centralized biometrics, by separating the custody of keys (done by the WFP) from the registry of biometric information linked to the individual's identity (managed by the UNHCR). Hence, from a privacy and security standpoint, WFP's Building Blocks incorporates the necessary safeguards to ensure that the merchant, the bank, the payment processor, the payment network, and other intermediaries are not exposed to information that is not relevant to their function. Indeed, the POS payment processor simply needs to know whether an individual has been enrolled in the system and whether the corresponding account balance is sufficient. It does not need to know the real-world identity, nor even the exact account balance of that individual⁴².

Moreover, for reduced security risks, the UNHCR does not store any personal identifying information (such as name, nationality, birthdate, sex, family relations, etc.) together with the biometric data in the BIMS database. All biometrics data is securely stored and completely segregated from

any other personal information. Likewise, BIMS does not store the information regarding the beneficiary's private keys—which are only accessible from the WFP's Building Blocks system. The privacy of refugees is therefore protected, since the WFP does not know the actual identity of the individuals whose transactions it processes, and the UNHCR does not have access to the transactions of the individuals it identifies.

Based on the success of the pilot, in January 2018, Building Blocks was scaled to serve all 106,000 Syrian refugees assisted by WFP in the Jordan camps. It is currently the largest implementation of blockchain technology for humanitarian aid in the world. To date, Building Blocks has processed USD 60 million of CBI through 3 million transactions and saved USD 900,000 in banking fees⁴³.

Next Steps

Everything described in the previous sections could be achieved with traditional databases. However, as blockchain is a relatively new and often theoretical concept in the humanitarian aid world, Building Blocks was a first step in demystifying some aspects of blockchain technology by demonstrating how the technology works at scale in the humanitarian context. As such, the Building Blocks programme was one of the first of its kind.

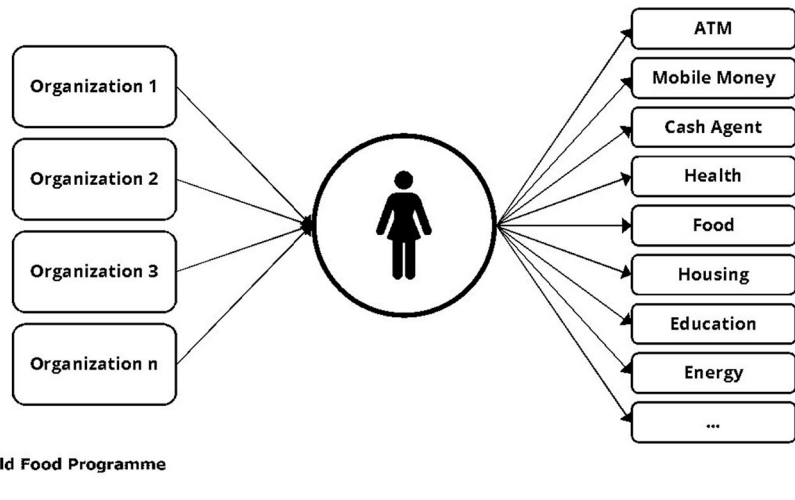
Having achieved that preliminary goal, Building Blocks now aims to take the next step by welcoming new members to the network, in order to facilitate seamless interaction with a variety of different agencies. Non-Governmental Organizations (NGOs) have particular security requirements in humanitarian contexts, and international NGOs are often struggling to reconcile the collection of large swathes of personal data for the issuance of digital identities across multiple agencies. In the Jordan refugee camps, for example, more than 45 organizations assist the same beneficiaries. Yet, the various systems are not meaningfully connected and interoperable. This results in duplication of effort and a somewhat fragmented view of the people served, who need to repeatedly disclose their personal information as they move between agencies.

If these organizations channeled their entitlements to each beneficiary's public key, there would be a unified view of the people served, creating opportunities for optimization and harmonization. Program designs and needs targeting could also become more equitable. Furthermore, all actors could be linked through a single connection to the blockchain, and the various outlets (such as food, cash, health, and education) could be combined. The elegance of the solution is that each organization could maintain its proprietary systems for registration, targeting, and entitlements manage, while still avoiding fragmentation.

⁴³The savings are achieved by performing all the "accounting" on the blockchain and only using the bank for making payments to merchants. The savings may or may not be replicable in other contexts depending on the operational realities on the ground.

⁴¹<https://www.unhcr.org/en-us/protection/basic/550c304c9/biometric-identity-management-system.html>

⁴²Note that in the Building Blocks system, the balance is printed at the bottom of beneficiary transaction receipts; and this is a feature that is much valued by the beneficiaries. However, because the transaction must be biometrically authorized by the beneficiary, the cashier cannot randomly query beneficiary balances, unless the beneficiary has triggered a transaction.



UN Women⁴⁴ is the first organization to join the Building Blocks network, and a joint pilot was launched in June 2019 to demonstrate precisely how two or more organizations can collaborate to assist the same people on a shared blockchain network. The model is intended to serve as the blueprint for broader collaboration.

UN Women (and each subsequent new member) operates an independent Building Blocks node, and each node validates and records every transaction on the network. Given that it cannot currently be assumed that all beneficiaries have smartphones and connectivity, Building Blocks has developed an innovative solution that allows each humanitarian provider on Building Blocks to be the custodian for the private keys related to their entitlements, while still maintaining a unified view of the people served on the blockchain. Building Blocks does not store any personally identifiable information on-chain.

Once the concept of entitlements unification on the blockchain is well-demonstrated and accepted, it is an easy step to move to identity attestations. One organization could, for example, attest that the owner of the public key is a nursing mother. Another organization could then search all the public keys for a “nursing mother” attestation and target services to those beneficiaries that fall within their mandate all without needing to know the sensitive personal information of the underlying people.

As the different pieces of a person’s identity puzzle are held by different actors, gaining collaboration based on a shared understanding of the technology and its potential for empowering the people served is fundamental in achieving meaningful blockchain-based identity by bringing all the pieces in one place. Building Blocks is taking the approach that the path to a full-fledged blockchain-based identity system is best started with the less sensitive components of identity. For example, insofar as CBI entitlements are determined and distributed in a siloed manner, the related transaction details are also fragmented across various systems and Financial Service Providers (FSP).

In such a scenario, if a credit agency wished to analyze the transaction data to assign a credit score for underwriting a loan, they would likely have access to only a portion of all the data. With fewer data points, statistical risk can be determined to a lower degree of accuracy, resulting in beneficiaries being charged a higher interest rate. Instead, if all entitlements were channeled to the unified blockchain wallet for each beneficiary and transactions were authorized from there, the financial transaction histories would also be unified. Based on this, an organization like Kiva, using a zero-knowledge-proof protocol, for example, could establish a credit rating for a beneficiary using all the data, resulting in a more favorable interest rate on the eventual loan. Furthermore, with Building Blocks, the data is portable, so if a Syrian refugee returns home, she could use the data generated in Jordan to get a small business loan in Syria and become self-sustaining again. Otherwise, the data is likely to stay behind with the FSPs in Jordan and would be inaccessible to the refugee back in Syria (or a new destination).

Like the Kiva protocol, Building Blocks also focuses first on the principles of interoperability and minimization, whereby multiple UN agencies can collaborate securely to have a unified view of the same beneficiary, but no personal identifying information is revealed on-chain, thereby protecting the privacy of the identity subject. Also like Kiva, given the conditions of the user population, self-custody is difficult and therefore not a priority at the start. In both cases, a blockchain-based identity infrastructure enables portability of attestations for migrant populations. Over time, additional use cases can be built on top of the identity system, such as using CBI transaction details across multiple UN agencies as data points to predict credit quality.

A question for the future is whether Kiva protocol may be interoperable with Building Blocks. Thus far, interoperability has been focused on actors within the use case e.g., microfinance institutions in Sierra Leone for Kiva and UN agencies for Building Blocks. The users of each identity system may overlap in the future, as these projects scale. For example, a participant (or former participant) in the Building Blocks program may seek microfinance loans in a jurisdiction that uses the Kiva

⁴⁴<http://www.unwomen.org/en>

1939 protocol. In bootstrapping her credit worthiness, would her CBI
 1940 transactions and attestations from Building Blocks be recognized
 1941 by the microfinance institutions participating in the Kiva
 1942 protocol? Recognition requires both policy agreements off-chain
 1943 and technical standards interoperability on-chain. Conversely, a
 1944 participant in the Kiva protocol may become a participant of
 1945 Building Blocks. Could her attestations from the Kiva protocol
 1946 be used in Building Blocks for various UN agencies to better
 1947 serve her needs? Could both of these identity systems allow other
 1948 trusted parties outside the initial set of permissioned nodes to
 1949 become attestors and nodes? Robust interoperability, technical
 1950 standards and policy alignments enable these identity systems
 1951 to have *composability* and *stackability*, whereby new applications
 1952 could be built on top of the base identity layer.

1954 FUTURE PERSPECTIVES

1956 As people become more and more mobile, a working identity
 1957 system that can operate on a global scale has become a
 1958 precondition for ensuring equal opportunities in the global
 1959 economy. As developing economies are rebuilding their identity
 1960 systems anew, it is important to be mindful of the consequences
 1961 that an improperly designed system might cause. The current
 1962 approaches of centralized governmental-based identity systems
 1963 relying on biometrics have serious limitations with regard to
 1964 both security and privacy (Prabhakar et al., 2003). A more
 1965 decentralized and self-sovereign identity system using verifiable
 1966 credentials and access controls is not only more flexible and
 1967 efficient, but can contribute to securing fundamental human
 1968 rights, especially in countries with unstable governments and
 1969 fragile institutions (Lemieux, 2017). Given their critical situation,
 1970 migrants, refugees and other vulnerable populations might
 1971 benefit from a system that enables them to selectively disclose
 1972 some attributes but not others, depending on the use cases.

1974 Dependence of Self-Sovereignty on 1975 Technology Infrastructure

1977 A true self-sovereign identity system would require a certain
 1978 level of infrastructure, primarily high penetration of affordable
 1979 smartphones that can securely store private keys and reliable
 1980 connectivity. Practitioners in the field, such as Kiva and the WFP,
 1981 recognize the realities of their constituents, who are vulnerable
 1982 populations in low infrastructure environments, many of whom
 1983 live below the poverty line. Therefore, it is not possible to assume
 1984 wide availability of the technical infrastructure and sophistication
 1985 for self-management of private keys.

1986 Another problem with localized key storage—beyond
 1987 hardware affordability—is the larger issue of key recovery,
 1988 since, in a self-managed environment, losing one's phone
 1989 necessarily entails losing one's private key. Hence, perhaps the
 1990 most important obstacle to achieving full self-sovereignty is the
 1991 problem of key recovery, combined with the price of hardware.

1992 In light of these issues, there is a consensus that the best
 1993 practice at the moment is a custody or guardianship model,
 1994 whereby program administrators like Kiva or WFP can manage
 1995 keys on behalf of constituents, but constituents always have

the ability to opt-out of guardianship should they choose
 to self-manage.

To address these challenges, some companies are moving
 into building the first generation of blockchain smartphones.
 HTC Exodus⁴⁵ is one of the first blockchain phones on the
 market, released in October 2018. The Exodus phone has its own
 trusted execution environment for secure key management and
 transaction signing. It deploys a social key recovery mechanism
 to recover private keys when the phone or passphrases are lost,
 whereby the user splits the private key among three to five trusted
 contacts⁴⁶. HTC is issuing a cheaper blockchain phone in Q3
 of 2019 called Exodus 1, which will be priced in the \$250–300
 range⁴⁷. While this would still be prohibitively expensive for
 many of Kiva's or WFP's constituents, it is a step in the right
 direction⁴⁸.

Digital Money and the Importance of Self-Sovereign Identity

The use of blockchain ledgers for peer-to-peer money transfer
 has numerous implications in development economics, further
 highlighting the need for self-sovereign identity solutions.
 One interesting application of blockchain technology is the
 digitization of local or complementary currencies as a natively
 digital cryptocurrency. Community currencies are usually softly
 pegged to the national currency, and therefore primarily function
 as a medium of exchange, rather than a store of value or unit
 of account.

For instance, Grassroots Economics⁴⁹ is a non-profit in Kenya
 that has been implementing a local currency program called
 Sarafu Credit with rural farmers since 2010. The Sarafu currency
 is softly pegged to the Kenyan shilling and is accepted by a
 local community of farmers, traders and schools. In communities
 where access to cash (Kenyan shillings) is difficult, bank accounts
 are inaccessible due to lack of identity documents, and mobile
 money providers like M-Pesa charge exorbitantly high fees,
 farmers are increasingly relying on local community currencies,
 as a complementary solution to the national currency (Dissaux
 and Ruddick, 2017).

Since October 2018, Grassroots Economics has turned Sarafu
 Credit into a stablecoin transacted on simple feature phones. A
 stablecoin is a cryptocurrency that is transacted on a blockchain
 ledger whose value is pegged to a national currency or a reference
 basket of assets. With the digitization of Sarafu credit as a
 stablecoin pegged to the Kenyan shilling, the transactions costs
 are significantly lower than both the paper version of Sarafu,
 and M-Pesa transactions. For instance, a 101 Kenyan shilling
 transaction will have a transaction fee of 11 shillings on M-Pesa,
 but only 2 shillings with Sarafu (the cost of two SMS, a USSD
 connection and negligible fees to run crypto transactions on an
 Ethereum side chain).

⁴⁵<https://www.htcexodus.com>

⁴⁶<https://www.wired.com/review/review-htc-exodus/>

⁴⁷<https://mashable.com/article/htc-exodus-1s-blockchain-phone/>

⁴⁸By comparison, the first cell phone from Motorola retailed for \$3,995 in 1982. Today, HTC, Samsung and others sell much more powerful smartphones for <\$200. See <https://www.timetoast.com/timelines/history-of-cellphones-prices>

⁴⁹<https://www.grassrootseconomics.org/>

2053 Most interestingly, transaction information which would
 2054 otherwise be owned and controlled by M-Pesa, or remain
 2055 untraceable with paper money, can now be recorded to a
 2056 blockchain. This data includes statistics on what kinds of goods
 2057 and services each wallet is spending its funds on, the transaction
 2058 sizes, and so forth. Such open source transaction data, when tied
 2059 to a self-sovereign identity system, would provide rich behavioral
 2060 information for purposes of underwriting microloans, micro-
 2061 insurance or other humanitarian applications such as needs
 2062 assessment planning to determine the amount of cash aid to
 2063 provide to beneficiaries. Traditionally, needs assessment is done
 2064 through focus groups and surveys. Dynamic data from live
 2065 transactions would be far more accurate, timely, and insightful
 2066 in ensuring that beneficiaries receive an adequate amount of cash
 2067 aid. Furthermore, as described under the Kiva model, if the loans
 2068 were disbursed and repaid using cryptocurrency, disbursement
 2069 and repayment claims could be automatically added to the Kiva's
 2070 identity protocol, thereby strengthening users' credit profile and
 2071 enhancing the richness of their digital identities.

2072 Grassroots Economics, Sempo (an Australian startup) and
 2073 the Red Cross are now working together on a new project
 2074 called Community Inclusion Currencies (CICs), which is a model
 2075 for channeling cash aid and other sources of philanthropic or
 2076 private sector cash as reserves that fractionally issue these local
 2077 currencies. Through a fractional reserve model, cash donations
 2078 and aid is effectively levered. For example, \$100 worth of cash
 2079 donation may be issued as \$120 worth of CICs. If the CICs
 2080 are circulated within the community at a high velocity, that
 2081 further amplifies the initial impact of the \$100 of cash aid. In
 2082 order to maintain price stability of the CICs, redemption of CICs
 2083 for the underlying cash can be gated algorithmically relative to
 2084 the existing supply of CICs, the issuance and redemption rates
 2085 of CICs, and the reserve ratio. The CICs would be issued as
 2086 a stablecoin pegged to the national currency, and ideally the
 2087 reserve would also be stored as a fiat-pegged stablecoin, with
 2088 issuance and redemption automated through smart contracts.
 2089 The CIC model could enable a scalable alternative mechanism
 2090 to community banks. For example, women's savings and loan
 2091 groups could deposit their collective savings into a reserve, and
 2092 whenever members need loans, the smart contract would issue
 2093 new CICs. Over time, interest and savings rates could be added
 2094 in order to make various CIC projects economically sustainable.
 2095 The CIC project was awarded a two year grant from Innovation
 2096 Norway, an arm of the Norwegian government, to pilot and scale
 2097 in Kenya and other locations globally⁵⁰.

2098 Stablecoins point to a future where money becomes
 2099 predominantly global and digital, but bankless (Balvers and
 2100 McDonald, 2017). Until the advent of cryptocurrency, digital
 2101 money necessarily meant bank-facilitated transactions, with
 2102 banks or other financial institutions (the gateways to the
 2103 banking rails) performing KYC and AML checks. Thus, those
 2104 without identity documents have been left out of the global
 2105 digital economy (Borio and Disyatat, 2010). As money becomes
 2106 increasingly global, there may be a concomitant opportunity
 2107 for the establishment of an equally global and digital identity

2110 management system that preserves the privacy of users (Vigna
 2111 and Casey, 2016), while adhering to compliance of global
 2112 regulatory regimes for KYC and AML. In particular, a synergy
 2113 might emerge between digital money and digital identity,
 2114 mediated through a blockchain-based infrastructure, whereby
 2115 transaction data can function as attestations that increase the
 2116 richness of a digital identity profile. This could contribute to
 2117 better credit underwriting, humanitarian needs assessment, and
 2118 more accurate (and ultimately more inclusive) risk assessments
 2119 for KYC/AML compliance.

2120 Identity Insurance as Backstop and 2121 Revenue Stream for Identity Providers? 2122

2123 Innovative ideas and new markets around digital identity have
 2124 yet to be realized. One interesting proposal explores creating
 2125 an insurance marketplace for consequential damages related
 2126 to identity claims⁵¹, which could be built on top of a digital
 2127 identity management system similar to Kiva's architecture. Such
 2128 a marketplace could provide the "last mile" assurance against
 2129 identity errors (e.g., bad data coming into the identity system)
 2130 and provide a market mechanism for evaluating the accurateness,
 2131 trustworthiness and usefulness of various claims associated with
 2132 an identity (Tang et al., 2003). This would enable lenders to
 2133 feel more comfortable underwriting a loan—particularly to an
 2134 individual with no formal credit history, if the claims associated
 2135 with that individual's profile were insured for consequential
 2136 losses toward the cost of the loan. Over time, traction in lending
 2137 activity would result in new attestations from the lender, thereby
 2138 increasing trust and lowering insurance premiums for that
 2139 particular individual.

2140 Identity insurance could also become a new revenue stream
 2141 for identity providers such as banks and microfinance lenders,
 2142 who are, in any case, required by law to conduct diligent
 2143 KYC checks. In such a semi-decentralized identity management
 2144 systems, banks, and lenders could underwrite the risk associated
 2145 with issuing an identity credential on the blockchain, thereby
 2146 helping subsequent lenders de-risk and creates economic
 2147 incentives for the lenders of "first resort"—(i.e., the lenders
 2148 willing to lend or issue identity credentials earlier in a borrower's
 2149 digital history).

2150 Refugees with little to no attestations might be subject to
 2151 higher risk premiums (because they have no track history)
 2152 until the refugees acquire more quality attestations so as to
 2153 make them more trustworthy. Such a model could encourage
 2154 refugees to engage as much as possible with specific institutions
 2155 or organizations, in order to collect a positive track record
 2156 of verifiable credentials, and therefore reduce the insurance
 2157 premium associated with their identity. In some cases, risk
 2158 premiums may even be subsidized by agencies like UNHCR
 2159 or other relevant organizations. Although such an insurance
 2160 model might ultimately be beneficial to refugees and displaced
 2161 individuals, who do not have a strong government to guarantee
 2162 for their identity, it should only be experimented after extensive
 2163 research has been done to mitigate any potential downside or
 2164 systemic risks of such an identity insurance, such as introducing

2108
 2109 ⁵⁰<http://news.trust.org/item/20191126123058-xtxvz/>

⁵¹<https://identityinsurance.org/>

illegal biases, discrimination or arbitrary value judgment into the underlying identity system.

CONCLUSION

Self-sovereign identity is a relatively new area of research, which is only now starting to materialize into real-world applications of new digital identity management systems. This is particularly valuable for applications that have the ability to scale and greatly improve financial and social inclusion of vulnerable populations (Blakstad and Allen, 2018). Yet, it is important to keep in mind that while there are emerging best practice standards and primitives for self-sovereign identity (McMullen et al., 2019), there is no generic identity protocol that solves all use cases. As demonstrated by the Kiva and WFP case studies, identity is inherently use case dependent. Interoperability and standardization will be important for scale, but the success of a particular identity application will depend on how its deployment is tailored to the use cases and local conditions. A successful identity management system will therefore need to be sufficiently flexible to adapt to the inherently malleable nature of human identity.

The development of cryptocurrencies as a new type of open source mobile money, particularly stablecoins, will enable users to benefit from an increased range of economic opportunities brought about by the new financial services built on top of these systems (Thomason et al., 2018). Verifiable credentials issued by trusted actors can function as identity claims. As described above, credentials signed by WFP to specific beneficiaries can serve as alternative credit scores, while organizations like Kiva can provide identity attestations. Likewise, Grassroots Economics, which currently manages the Sarafu program in Kenya, could sign identity claims on behalf of its participants based on Sarafu transactions, which could help its constituents graduate into Kiva's identity protocol and microfinance ecosystem.

Ultimately, Kiva could provide loan capital in a stablecoin to its microfinance partners, via a peer-to-peer transaction that is cheaper and faster compared to international money transfer via correspondent banking (Darlington, 2014). The microfinance lenders could directly disburse loans in a stablecoin denominated in the local currency of the borrower. The microfinance lenders on Kiva's identity protocol would then automatically sign identity claims in regards to disbursements and loan repayments, as such transactions are now verifiable on-chain, thereby reducing potential disputes. Borrowers could subsequently use these loans for their business needs: purchasing inventory for their shop, paying wages to their employees, and so on. As a result, previous and successfully repaid loans would function as identity

REFERENCES

- Alvarez, R. M., Hall, T. E., and Trechsel, A. H. (2009). Internet voting in comparative perspective: the case of Estonia. *Pol. Sci. Polit.* 42, 497–505. doi: 10.1017/S1049096509090787
- Androulaki, E., Karame, G. O., Roeschlin, M., Scherer, T., and Capkun, S. (2013). "Evaluating user privacy in bitcoin," in *International Conference on*

attestations, further enriching the digital history and credit profile of the borrowers, and creating a virtuous circle for financial inclusion. These new identity business models, such as identity insurance, would likely arise out of this mobile money/identity ecosystem, further enhancing the robustness of the ecosystem as a whole. And while we are still far from having a truly digital, global and self-sovereign identity system, we believe that blockchain technology could be one of the key building blocks to instantiate this vision.

DATA AVAILABILITY STATEMENT

No datasets were generated or analyzed for this study.

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AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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- Financial Cryptography and Data Security* (Berlin; Heidelberg: Springer), 34–51. doi: 10.1007/978-3-642-39884-1_4
- Araújo, L. C., Sucupira, L. H., Lizarraga, M. G., Ling, L. L., and Yabu-Uti, J. B. T. (2005). User authentication through typing biometrics features. *IEEE Trans. Signal Process.* 53, 851–855. doi: 10.1109/TSP.2004.839903
- Aydar, M., and Ayvaz, S. (2019). Towards a Blockchain based digital identity verification, record attestation and record sharing system. *arXiv preprint arXiv:1906.09791*.

- Q17 2281 Baars, D. S. (2016). *Towards self-sovereign identity using blockchain technology* (Master's thesis). University of Twente.
- 2282
- 2283 Balvers, R. J., and McDonald, B. (2017). *Designing a Global Digital Currency*. Available online at SSRN: <https://ssrn.com/abstract=3049000>
- 2284
- Q18 2285 Bhargav-Spantzel, A., Squicciarini, A., Bertino, E., Kong, X., and Zhang, W. (2010). "Biometrics-based identifiers for digital identity management," in *Proceedings of the 9th Symposium on Identity and Trust on the Internet* (ACM), 84–96. doi: 10.1145/1750389.1750401
- 2286
- 2287
- Q19 2288 Blakstad, S., and Allen, R. (2018). "Leapfrogging banks in emerging markets," in *FinTech Revolution* (Cham: Palgrave Macmillan), 121–132. doi: 10.1007/978-3-319-76014-8_7
- 2289
- 2290 Blazewicz, J., Kubiak, W., Morzy, T., and Rusinkiewicz, M. (eds.). (2012). *Handbook on Data Management in Information Systems*. Springer Science and Business Media.
- 2291
- Q18 2292 Borio, C., and Disyatat, P. (2010). Global imbalances and the financial crisis: reassessing the role of international finance. *Asian Econ. Policy Rev.* 5, 198–216. doi: 10.1111/j.1748-3131.2010.01163.x
- 2293
- 2294
- 2295
- 2296 Burge, T. (1988). Individualism and self-knowledge. *J. Philos.* 85, 649–663. doi: 10.5840/jphil1988851112
- 2297
- Q18 2298 Bygrave, L. A. (2012). *The Data Difficulty in Database Protection*. University of Oslo Faculty of Law Research Paper (2012-18).
- 2299
- 2300 Côté, J. E. (1996). Sociological perspectives on identity formation: the culture-identity link and identity capital. *J. Adolescence* 19, 417–428. doi: 10.1006/jado.1996.0040
- 2301
- 2302 Campisi, P. (2013). *Security and Privacy in Biometrics, Vol. 24*. London: Springer. doi: 10.1007/978-1-4471-5230-9
- 2303
- 2304 Canham, J. (2018). Biometrics: leap of faith or fact of life?. *Biometr. Technol. Today* 2018, 8–10. doi: 10.1016/S0969-4765(18)30024-9
- 2305
- Q19 2306 Cap, C. H., and Maibaum, N. (2001). "Digital identity and its implication for electronic government," in *Towards the E-Society* (Boston, MA: Springer), 803–816. doi: 10.1007/0-306-47009-8_59
- 2307
- 2308 Christman, J. (2013). Social practical identities and the strength of obligation. *J. Soc. Philos.* 44, 121–123. doi: 10.1111/josp.12024
- Q20 2309 2310 Darlington, J. K. III. (2014). *The future of Bitcoin: mapping the global adoption of world's largest cryptocurrency through benefit analysis*.
- 2311
- 2312 Davidson, S., De Filippi, P., and Potts, J. (2016). *Economics of Blockchain*. Available online at SSRN: <https://ssrn.com/abstract=2744751>
- Q21 2313 2314 De Filippi, P. (2014). Bitcoin: a regulatory nightmare to a libertarian dream. *Internet Policy Rev.* 3. doi: 10.14763/2014.2.286
- Q22 2315 2316 De Filippi, P. (2015). "Translating commons-based peer production values into metrics: toward commons-based cryptocurrencies," in *Handbook of Digital Currency* (Academic Press), 463–483. doi: 10.1016/B978-0-12-802117-0.00023-0
- Q16 2317 2318 De Filippi, P. (2016). The interplay between decentralization and privacy: the case of blockchain technologies. *J. Peer Prod.* 7:al-01382006.
- Q21 2319 2320 De Filippi, P., and Loveluck, B. (2016). The invisible politics of bitcoin: governance crisis of a decentralized infrastructure. *Internet Policy Rev.* 5. doi: 10.14763/2016.3.427
- Q24 2321 2322 De Filippi, P., and Mauro, R. (2014). Ethereum: the decentralised platform that might displace today's institutions. *Internet Policy Rev.* 25.
- Q18 2323 2324 De Filippi, P., and Wright, A. (2018). *Blockchain and The Law: The Rule of Code*. Harvard University Press. doi: 10.2307/j.ctv2867sp
- 2325
- Q16 2326 Der, U., Jähnichen, S., and Sürmeli, J. (2017). Self-sovereign identity \$-\$ opportunities and challenges for the digital revolution. *arXiv preprint arXiv:1712.01767*.
- 2327
- 2328 Dissaux, T., and Ruddick, W. (2017). "Challenges of collective organization and institution building around community currencies in Kenyan slums," in *4th International Conference on Social and Complementary Currencies* (Barcelona).
- 2329
- 2330 Dunphy, P., and Petitcolas, F. A. (2018). A first look at identity management schemes on the blockchain. *IEEE Secur. Priv.* 16, 20–29. doi: 10.1109/MSP.2018.3111247
- 2331
- 2332 Duta, N. (2009). A survey of biometric technology based on hand shape. *Pattern Recogn.* 42, 2797–2806. doi: 10.1016/j.patcog.2009.02.007
- 2333
- 2334 Eakin, P. J. (1999). *How Our Lives Become Stories: Making Selves*. Cornell University Press.
- Q18 2335 2336 2337 El Haddouti, S., and El Kettani, M. D. E. C. (2019). "Analysis of identity management systems using blockchain technology," in *2019 International Conference on Advanced Communication Technologies and Networking (CommNet)* (Rabat: IEEE), 1–7. doi: 10.1109/COMMNET.2019.8742375
- 2338
- 2339 2340 Freund, A. (2018). "Automated, decentralized trust: a path to financial inclusion," in *Handbook of Blockchain, Digital Finance, and Inclusion, Vol. 1* (Academic Press), 431–450. doi: 10.1016/B978-0-12-810441-5.00030-0
- 2341
- 2342 2343 Friedman, A., Crowley, P., and West, D. (2011). *Online Identity and Consumer Trust: Assessing Online Risk*. The Brookings Institution, 11.
- 2344
- Q18 2345 2346 Ganapathy, V., Thomas, D., Feder, T., Garcia-Molina, H., and Motwani, R. (2011). "Distributing data for secure database services," in *Proceedings of the 4th International Workshop on Privacy and Anonymity in the Information Society* (ACM), 8. doi: 10.1145/1971690.1971698
- 2347
- 2348 Garcia, P. (2018). Biometrics on the blockchain. *Biometr. Technol. Today* 2018, 5–7. doi: 10.1016/S0969-4765(18)30067-5
- 2349
- Q18 2350 2351 Garrett, B. (2002). *Personal Identity and Self-Consciousness*. Routledge. doi: 10.4324/9780203015667
- 2352
- Q21 2353 2354 Geach, P. (1973). "Ontological relativity and relative identity," in *Logic and Ontology*, ed. M. K. Munitz (New York, NY: New York University Press).
- 2355
- Q22 2356 2357 Gencer, M. (2011). The mobile money movement: catalyst to jump-start emerging markets. *Innovations* 6, 101–117. doi: 10.1162/INOV_a_00061
- 2358
- 2359 Gentry, C., and Boneh, D. (2009). *A Fully Homomorphic Encryption Scheme, Vol. 20, No. 09*. Stanford, CA: Stanford University.
- 2360
- Q25 2361 2362 Gerard, D. (2017). Attack of the 50 foot blockchain: bitcoin, blockchain, Ethereum and smart contracts.
- Q20 2363 2364 Gleick, P. (2014). *Water, Drought, Climate Change, and Conflict in Syria*. Oakland, CA: Pacific Institute. Available online at: <https://journals.ametsoc.org/doi/full/10.1175/WCAS-D-13-00059.1> (accessed July 1, 2014).
- 2365
- 2366 Goldreich, O. (1998). *Secure Multi-Party Computation. Preliminary version*, 78.
- 2367
- Q25 2368 2369 Guides, T. S. (2019). *How Do Stablecoins Work*.
- Q20 2370 2371 Hammudoglu, J. S., Sparreboom, J., Rauhamaa, J. I., Faber, J. K., Guerchi, L. C., Samiotis, I. P., et al. (2017). Portable Trust: biometric-based authentication and blockchain storage for self-sovereign identity systems. *arXiv preprint arXiv:1706.03744*.
- Q22 2372 2373 Hardjono, T., and Pentland, A. (2019). Verifiable anonymous identities and access control in permissioned blockchains. *arXiv preprint arXiv:1903.04584*.
- Q16 2374 2375 Hileman, G., and Rauchs, M. (2017). Global cryptocurrency benchmarking study. *SSRN Electron. J.* 33. doi: 10.2139/ssrn.2965436
- 2376
- Q21 2377 2378 Jacobovitz, O. (2016). *Blockchain for Identity Management*. The Lynne and William Frankel Center for Computer Science Department of Computer Science, Ben-Gurion University, Beer Sheva Google Scholar, 9.
- 2379
- Q18 2380 2381 Jain, A. K., Flynn, P., and Ross, A. A. (Eds.). (2007). *Handbook of Biometrics*. Springer Science and Business Media. doi: 10.1007/978-0-387-71041-9
- 2382
- Q16 2383 2384 Jain, A. K., and Nandakumar, K. (2012). Biometric authentication: system security and user privacy. *IEEE Comp.* 45, 87–92. doi: 10.1109/MC.2012.364
- Q22 2385 2386 Jain, A. K., Ross, A., and Prabhakar, S. (2004). An introduction to biometric recognition. *IEEE Trans. Circuits Syst. Video technol.* 14. doi: 10.1109/TCSVT.2003.818349
- 2387
- Q21 2388 2389 Jenkins, B. (2008). *Developing Mobile Money Ecosystems*. Washington, DC: International Finance Corporation and Harvard Kennedy School.
- 2390
- Q18 2391 2392 Jøsang, A., and Pope, S. (2005). "User centric identity management," in *AusCERT Asia Pacific Information Technology Security Conference*, 77.
- 2393
- 2394 Khare, R., and Rifkin, A. (1997). Weaving a web of trust. *World Wide Web J.* 2, 77–112.
- 2395
- Q18 2396 2397 Kosta, E. (2013). *Consent in European Data Protection Law*. Martinus Nijhoff Publishers. doi: 10.1163/9789004232365
- 2398
- Q16 2399 2400 Kulkarni, M. H., Yadav, A., Shah, D., Bhandari, P., and Mahapatra, S. (2012). Unique id management. *Int. J. Comp. Technol. Appl.* 3, 520–524.
- 2401
- Q22 2402 2403 Lee, S. (2018). *Explaining Stable Coins, The Holy Grail of Cryptocurrency*. Available online at: <https://www.forbes.com/sites/shermanlee/2018/03/12/explaining-stable-coins-the-holygrail-of-cryptocurrency>
- 2404
- Q18 2405 2406 Lemieux, V. L. (2017). "In blockchain we trust? Blockchain technology for identity management and privacy protection," in *Conference for E-Democracy and Open Government*, 57.
- 2407
- 2408 Maesa, D. D. F., Mori, P., and Ricci, L. (2017). "Blockchain based access control," in *IFIP International Conference on Distributed Applications and Interoperable Systems* (Cham: Springer), 206–220. doi: 10.1007/978-3-319-59665-5_15
- 2409
- Q18 2410 2411 McMullen, G., De Filippi, P., and Choi, C. (2019). *Blockchain Identity Services: Technical Benchmark of Existing Blockchain-Based Identity Systems*. COALA and BRI Big Idea Whitepaper.

- 2395 Mordini, E., and Massari, S. (2008). Body, biometrics and identity. *Bioethics* 22, 2396 488–498. doi: 10.1111/j.1467-8519.2008.00700.x
- 2397 Mühle, A., Grüner, A., Gayvoronskaya, T., and Meinel, C. (2018). A survey on 2398 essential components of a self-sovereign identity. *Comput. Sci. Rev.* 30, 80–86. 2399 doi: 10.1016/j.cosrev.2018.10.002
- Q18 2399 Muller, B. J. (2010). *Security, Risk and the Biometric State: Governing Borders and* 2400 *Bodies*. Routledge. doi: 10.4324/9780203858042
- Q23 2401 Nagar, A., Nandakumar, K., and Jain, A. K. (2010). “Biometric template 2402 transformation: a security analysis,” in *Media Forensics and Security II*, 2403 *Vol. 7541* (International Society for Optics and Photonics), 75410O. 2404 doi: 10.1117/12.839976
- Q22 2404 Ngugi, B., Pelowski, M., and Ogembo, J. G. (2010). M-pesa: a case study 2405 of the critical early adopters role in the Rapid adoption of mobile 2406 money banking in Kenya. *Electron. J. Inform. Syst. Dev. Ctries.* 43, 1–16. 2407 doi: 10.1002/j.1681-4835.2010.tb00307.x
- Q22 2407 Nguyen, Q. K. (2016). “Blockchain—a financial technology for future sustainable 2408 development,” in *2016 3rd International Conference on Green Technology and* 2409 *Sustainable Development (GTSD)* (IEEE), 51–54. doi: 10.1109/GTSD.2016.22
- Q18 2410 O’Gorman, L. (2003). Comparing passwords, tokens, and biometrics for user 2411 authentication. *Proc. IEEE* 91, 2021–2040. doi: 10.1109/JPROC.2003.819611
- Q18 2412 Othman, A., and Callahan, J. (2018). “The Horcrux protocol: a method 2413 for decentralized biometric-based self-sovereign identity,” in *2018* 2414 *International Joint Conference on Neural Networks (IJCNN)* (IEEE), 1–7. 2415 doi: 10.1109/IJCNN.2018.8489316
- 2415 Prabhakar, S., Pankanti, S., and Jain, A. K. (2003). Biometric recognition: 2416 security and privacy concerns. *IEEE Secur. Priv.* 1, 33–42. 2417 doi: 10.1109/MSECP.2003.1193209
- 2418 Proença, H., and Alexandre, L. A. (2010). Iris recognition: analysis of the error 2419 rates regarding the accuracy of the segmentation stage. *Image Vision Comput.* 28, 202–206. doi: 10.1016/j.imavis.2009.03.003
- 2420 Rane, S., Wang, Y., Draper, S. C., and Ishwar, P. (2013). Secure biometrics: 2421 concepts, authentication architectures, and challenges. *IEEE Signal Process.* 2422 *Mag.* 30, 51–64. doi: 10.1109/MSP.2013.2261691
- Q18 2422 Rannenber, K., Camenisch, J., and Sabouri, A. (2015). *Attribute-Based* 2423 *Credentials for Trust. Identity in the Information Society*. Springer. 2424 doi: 10.1007/978-3-319-14439-9
- Q18 2425 Ross, A., and Jain, A. K. (2004). “Multimodal biometrics: an overview,” in *2004* 2426 *12th European Signal Processing Conference* (IEEE), 1221–1224.
- 2427 Sarkar, S. (2014). The unique identity (UID) project, biometrics and 2428 re-imagining governance in India. *Oxf. Dev. Stud.* 42, 516–533. 2429 doi: 10.1080/13600818.2014.924493
- 2430 Schartner, P., and Schaffer, M. (2005). “Unique user-generated digital 2431 pseudonyms,” in *International Workshop on Mathematical Methods, Models,* 2432 *and Architectures for Computer Network Security* (Berlin; Heidelberg: Springer), 2433 194–205. doi: 10.1007/11560326_15
- 2434 Schneier, B. (1999). The uses and abuses of biometrics. 2435 *Commun. ACM.* 42, 136–136. doi: 10.1145/310930.310988
- Q16 2434 Shrier, D., Wu, W., and Pentland, A. (2016). Blockchain and infrastructure 2435 (identity, data security). *Mass. Inst. Technol. Connect. Sci.* 1, 1–19.
- 2436 Strohminger, N., Knobe, J., and Newman, G. (2017). The true self: a 2437 psychological concept distinct from the self. *Perspect. Psychol. Sci.* 12, 551–560. 2438 doi: 10.1177/1745691616689495
- 2439 Suler, J. R. (2002). Identity management in cyberspace. *J. Appl. Psychoanal. Stud.* 4, 2440 455–459. doi: 10.1023/A:1020392231924
- 2441
- 2442
- 2443
- 2444
- 2445
- 2446
- 2447
- 2448
- 2449
- 2450
- 2451
- 2452
- 2453
- 2454 Tang, F. F., Thom, M. G., Wang, L. T., Tan, J. C., Chow, W. Y., and Tang, X. (2003). 2455 Using insurance to create trust on the internet. *Commun. ACM* 46, 337–344. 2456 doi: 10.1145/953460.953519
- 2457 Team, M. (2017). *The Dai Stablecoin System*. Available online at: <https://makerdao.com/whitepaper/DaiDec17WP.Pdf> Q22 2458
- 2459 Thomason, J., Ahmad, M., Bronder, P., Hoyt, E., Pocock, S., Bouteloupe, 2460 J., et al. (2018). “Blockchain—powering and empowering the poor 2461 in developing countries,” in *Transforming Climate Finance and* 2462 *Green Investment with Blockchains* (Academic Press), 137–152. 2463 doi: 10.1016/B978-0-12-814447-3.00010-0
- 2464 Tikkinen-Piri, C., Rohunen, A., and Markkula, J. (2018). EU general data 2465 protection regulation: changes and implications for personal data collecting 2466 companies. *Comput. Law Sec. Rev.* 34, 134–153. doi: 10.1016/j.clsr.2017.05.015
- 2467 Tobin, A., and Reed, D. (2016). *The Inevitable Rise of Self-Sovereign Identity*. The 2468 Sovrin Foundation, 29. Q18 2469
- 2470 Toth, K., and Subramaniam, M. (2003). “The persona concept: a consumer- 2471 centered identity model,” in *3rd International Workshop on Emerging* 2472 *Applications for Wireless and Mobile Access (MobEA)* (Budapest). 2473
- 2474 Uludag, U., Ross, A., and Jain, A. (2004). Biometric template selection 2475 and update: a case study in fingerprints. *Pattern Recogn.* 37, 1533–1542. 2476 doi: 10.1016/j.patcog.2003.11.012
- 2477 Unar, J. A., Seng, W. C., and Abbasi, A. (2014). A review of biometric 2478 technology along with trends and prospects. *Pattern Recogn.* 47, 2673–2688. 2479 doi: 10.1016/j.patcog.2014.01.016
- 2480 van der Ploeg, I. (2003). “Biometrics and the body as information,” in *Surveillance* 2481 *as Social Sorting: Privacy, Risk and Digital Discrimination*, 57–73. 2482
- 2483 van Wingerde, M. (2017). *Blockchain-enabled self-sovereign identity* (Doctoral 2484 dissertation, Master’s thesis). Tilburg University, School of Economics 2485 and Management. Q17 2486
- 2487 Vigna, P., and Casey, M. J. (2016). *The Age of Cryptocurrency: How Bitcoin and the* 2488 *Blockchain Are Challenging the Global Economic Order*. Macmillan. 2489
- 2490 Werz, M., and Conley, L. (2012). *Climate Change, Migration, and Conflict in* 2491 *Northwest Africa*. Center for American Progress, 8. Q18 2492
- 2493 Whitley, E. A., and Hosein, G. (2010). Global identity policies and 2494 technology: do we understand the question?. *Global Policy* 1, 209–215. 2495 doi: 10.1111/j.1758-5899.2010.00028.x
- 2496 Wright, A., and De Filippi, P. (2015). *Decentralized Blockchain Technology and the* 2497 *Rise of Lex Cryptographia*. Available online at SSRN: <https://ssrn.com/abstract=2580664> 2498
- 2499 Zibran, M. F. (2012). *Biometric Authentication: The Security Issues*. University 2500 of Saskatchewan. Q18 2501
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The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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