COVID-19 Antibody Test Certification "There's An App For That"

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Executive summary/abstract: As the Coronavirus Pandemic of 2019/2020 unfolds, a COVID-19 'Immunity Passport' has been mooted as a way to enable individuals, especially those in healthcare and other key industries, to return safely back to work at 'the right moment'. Despite a number of ethical, social, legal, and biological dilemmas (e.g. 'COVID-19 antibody testing' is itself unproven), verifiable test results could well become highly desirable, at least in certain key sectors. But a 'paper certificate' has a number of dilemmas of its own, including weak tamper-proofness and rather arcane and clumsy verifiability. To address many of the underlying issues involved in certification, and as a proof of concept for future pandemics, we have developed a prototype mobile phone app that facilitates instant verification of tamper-proof test results. Personally identifiable information is only stored at the user's discretion, and the app allows the end-user selectively to present only the specific test result with no other personal information revealed. Behind the scenes it relies upon (a) the 2019 World Wide Web Consortium standard called 'Verifiable Credentials', (b) Tim Berners-Lee's decentralised personal data platform 'Solid', and (c) a consortium Ethereum-based blockchain. These enable the aforementioned mixture of verifiability and privacy in a manner derived from public/private key pairs and digital signatures, generalised to avoid restrictive ownership of sensitive digital keys and/or data. We describe the underlying principles, ethical considerations, and a 9-step use case scenario.

1. The idea: a certificate of immunity

The Coronavirus/COVID-19 pandemic of 2019/2020 is still in its frightening global exponential growth phase as we write this, and has already led to massive loss of life, illness, unemployment, business collapse, and social malaise -- actual numbers are moving too quickly to report, but are easily accessible via many resources, including the well-known Johns Hopkins visualisation/dashboard [1]. In addition to the 'test-isolate-trace' approach strongly urged by the World Health Organisation [2], there is also an ongoing effort to test people for the presence of antibodies (and a likely strong degree of immunity) in the hope that individuals could be allowed to get back to work, particularly in healthcare and other key areas [3]. In late March / early April, the UK Secretary of State for Health and Social Care stated that the UK Government's aim is to end the present lockdown through the use of 'Immunity Passports' [3, 4].

Aside from the social, ethical and legal implications of issuing 'Immunity Passports' (which are raised in [5], and to which we return below — particularly focusing on the ethical issues in Section 7), there are challenges concerning the fundamental biological premise of 'immunity': the strength and longevity of Coronavirus immunity after infection are matters of current debate and research. Some immunologists argue that Coronavirus immunity could be very weak, because 'reinfection is an issue with the four seasonal coronaviruses that cause about 10% to 30% of common colds' [6]. Others in that same discussion argue that immunity could be valid for 'a year or two', a view shared by Male, who with Golding and Bootman has written a clear exposition on the life-cycle of infection, antibody detection, and likely immunity to COVID-19 [7]. The *sensitivity* (% positive detection for the right antibodies, so high sensitivity means few false positives) and *specificity* (% negatives correctly detected, so high specificity means false negatives are few) of the tests are undergoing great scrutiny even as we write this, and are of course a matter of concern, as they must be sufficiently high to make the approach worthwhile.

Our view is that, while test sensitivity and specificity, as well as the strength and longevity of immunity, continue to be researched, the return-to-work scenario raised in the paragraphs above will inevitably require certification in some form, whether 'strong' (e.g. Immunity Passports) or 'weak' (e.g. notes/letters/signatures from healthcare or pharmacy professionals). Even if such certification turns out to be inappropriate or unusable for this COVID-19 outbreak, then the concept might well be applicable to some future pandemic. There are two obvious different antibody test scenarios for the current and future pandemics: such tests will either (a) be self-administered via home test kits (making it difficult to oversee and 'prove' results), or (b) be administered by well-respected authorities such as doctors and/or nurses at GP surgeries within the remit of the NHS in the UK or pharmacies with proven track records of vaccinations and other related activities (making certifiable results achievable).

Given the scale of the current pandemic and the financial hardship unfolding, it is plausible that 'COVID-19 antibody test certification' (henceforth 'CATC') will be in great demand. It is not too far-fetched to imagine that such demand would generate social, ethical and legal controversies, not least of which being a potential socio-economic 'have/have-not' divide (see [5] and our discussion of ethical considerations in Section 7), and perhaps a certain degree of fraud and forgery. Even in the absence of outright forgery attempts, and even in the absence of immunologically-proven 'strong immunity', we feel that for either the current pandemic or a pandemic of the future, the concept of certification has a place, *particularly when the recipient is employed in healthcare or other nationally-agreed key sectors*.

2. Benefits of a Digital Certificate

What form should such a certificate take? A signed or stamped letter is the centuries-old default, and straightforward to roll out at scale, as long as there is some point-of-test proof of identity. But for such a sensitive and (likely to be) valuable certificate, a digital certificate makes considerably more sense, provided that it satisfies the following criteria:

- Must preserve **privacy** (does not give away any personally-identifiable sensitive data).
- Must be **secure** (e.g. cannot be 'cloned' easily).
- Must be easy to **administer** by the tester (with relatively few digital skills required).
- Must be easily **verifiable** by those who need to know (e.g. employer, healthcare unit), while still preserving privacy.
- Must be **scalable** to millions of users.
- Must be **cost-effective**.

Superficially, both paper and digital methods can deal with all of these criteria, but closer inspection reveals some key differences, as the table below highlights.

	Paper	Digital
Private	Yes if carefully guarded; no if too much personal info is printed on the document	Yes with selective reveal of only user-chosen info, as long as modern encryption used
Secure	Only if carefully held by owner	Yes if modern encryption used
Easy admin	Yes, but slow, with duplicate filing of records if needed	Yes if mobile app and QR code scan
Verifiable	Yes, if certificate 'looks good' and individual shows ID, BUT could be difficult to print certificates that can not easily be recreated/cloned	Yes if mobile app and QR code scan
Scalable	Yes because 'devil-you-know' but very tedious	Yes if 'culture of use' accepts mobile scanning
Cost-effective	Cheap 'devil-you-know' but expensive and error-prone	Could be costly up-front, but cheap long-term

 Table 1. Paper vs Digital Certificates.

Naturally both paper and digital approaches can be used side-by-side, since there may be a certain degree of unease about a wholly-digital certificate (not unlike the phenomenon of using printed train or cinema tickets and mobile app e-tickets as acceptance and comfort levels grow). We believe that the digital certificate can be enhanced with unique properties that will make it particularly attractive to people, as long as it is kept in an easy-to-use mobile app: (a) it will allow individuals to take **ownership** of their own test result certification — the test results will reside with them, on their mobile phone, and optionally (at their discretion) in a secure cloud repository of their choice, plus a cryptographic 'thumbprint' stored in a blockchain for verification purposes, as described in Section 3; (b) they will be able to provide **evidence** of test result certification at their own discretion to multiple authorities such as employers, security forces, or government agencies as-and-when appropriate; (c) they will be able to **selectively reveal** parts of their certificate without necessarily surrendering other personal/sensitive details which might otherwise appear on a standard printed letter or potentially onerous 'Big Brother'-ish apps. The next section explains the principles for achieving digital certification.

3. A route to digital certification and verification

3.1 Verifiable Credentials

In April 2017 a task force within the World Wide Web Consortium¹ known as the 'W3C Verifiable Claims Working Group' came together to address the problem of standards for digital credentials, and by November 2019 had put forward a standard called 'Verifiable Credentials' [9] specifically designed to deal with certification in a secure and privacy-preserving manner. The main ideas are built upon existing well-known tools and concepts such as the Public Key Infrastructure (PKI) that underlies the public/private key pairs that facilitate digital signatures in widespread use today. The W3C extensions are designed to standardise the definitions of document formats in a flexible manner that allow them to be machine-readable and communicable, and to generalise PKI, which tends to be costly and highly centralised. The generalisation moves to a decentralised/distributed registry for cryptographic keys, typically (but not necessarily) residing in a blockchain because this allows every public key to have its own unique address: such an address is known as a Decentralised Identifier (DID). The key roles and transactions are illustrated in Figure 1, with comments below the figure.



Figure 1. Main roles and workflow in W3C Verifiable Credentials, based on [9].

In Figure 1, the upper left of the main diagram shows an 'Issuer', which might be a bank, or the NHS, or a University, or anyone issuing certificates, licenses, or credentials. The Issuer can

¹ The World Wide Web Consortium (W3C) describes itself as 'an international community where Member organizations, a full-time staff, and the public work together to develop Web standards. Led by Web inventor and Director Tim Berners-Lee and CEO Jeffrey Jaffe, W3C's mission is to lead the Web to its full potential.' From [8].

create credentials, while 'Holders' (typically citizens as end-users in this diagram) can store them in their own preferred way, for example in digital 'wallets' that are part of a mobile phone app. 'Verifiers', such as employers, or even shops or pubs seeking proof of age, can ask the Holder to present such proof concerning these credentials — known as 'verifiable presentations' which are collections of evidence (such as credentials or pieces of data derived from credentials). Verifiers also confirm which Issuers have attested some claim or credential by checking digital signatures against what is known as a 'verifiable data registry'. According to the W3C [9]:

A 'verifiable data registry' is a role a system might perform by mediating the creation and verification of identifiers, keys, and other relevant data, such as verifiable credential schemas, revocation registries, Issuer public keys, and so on, which might be required to use verifiable credentials. Some configurations might require correlatable identifiers for subjects. Example verifiable data registries include trusted databases, decentralized databases, government ID databases, and distributed ledgers. Often there is more than one type of verifiable data registry utilized in an ecosystem.

The Verifiable Data Registry is typically (but not necessarily) a blockchain. Figure 2 below illustrates the specific case of storing Decentralised Identifiers (DIDs), and using them for signing claims, countersigning claims, and verifying signatures among the other examples used in the definition of Verifiable Data Registry immediately above.



Figure 2. DIDs and Blockchain, based on [10]: every Decentralised ID has an associated public-private key pair, so anyone with a DID can issue and sign verifiable claims and other documents. As long as the Verifier has the DID of the Issuer (typically stored within the credential itself), it is easy to look up the Issuer's public key on the blockchain and verify the signature on the claims. Such a look-up does not involve any transactions, and thus incurs neither delay nor payment.

3.2 Decentralised Verification of Data with Confidentiality

We pointed out in [11] that the over-centralisation of data, particularly its consolidation into 'silos' by name-brand IT services and social network providers, is of growing concern. We noted a growing interest in decentralisation because of its perceived benefits in areas involving the storage of sensitive data, including medical, financial and other personal data, where data integrity and accessibility were deemed by individuals to be of utmost importance.

With various decentralised approaches having their own obstacles to mainstream deployment, we identified a valuable approach, known as Solid, initiated by Sir Tim Berners-Lee [12, 13]. Solid aims to decentralise the Web by transferring control of data from a central authority to users, thereby allowing users to retain complete ownership of their data, which they store in what are called 'Solid Pods' — this avoids companies storing an individual's personal data on their servers, and instead allows individuals to keep such data on their own personal data 'pods', analogous to a personal website that can be hosted locally, including within a mobile phone app, or with a known provider, with backup on a cloud server of the individual's choice, or both, at the individual's discretion. The key distinction from centralised approaches (e.g., social media profiles) is that even in the provider-hosted case, the provider's access to the data is limited by the user's choice.

In [14] we proposed an approach combining 'Solid Pods' and distributed ledgers, of the type familiar to the blockchain community, to facilitate the complete decentralisation of data. The key ingredients of this combination are illustrated in Figure 3 below. The figure 'foreshadows' elements of our specific solution for COVID-19 certificates discussed further below, but since the underlying architecture is independent of the specific example we use the same notation to make it concrete. Our methods give users total control over their data while maintaining the integrity of the stored information through Blockchain-based verification.



Figure 3. Solid Pod hosted on mobile and/or cloud, with minimal hash storage for verification.

As in earlier figures, and the scenario further below, 'Holder' is the primary individual who is self-motivated to obtain (and 'hold') the certificate of COVID-19 immunity in order to be admitted to a workplace or other key location. In the scenario below and indeed in any other scenario based on our architecture, Holders own, manage and control their own Solid Pods, which contain their personal data. In Figure 3 above, our Holder's Solid Pod contains a scanned image of a physical ID such as a driving licence (used as we shall see below for proof of identity) and the Holder's signed and countersigned certificate of COVID-19 Immunity certification represented in Figure 3 as a 'document' in which is embedded a special QR code. Unlike typical apps that the public uses daily, the Holder is free to store the Solid Pod data on his/her mobile, on a personal favourite Cloud provider, or both, as shown in the 'Hosted' arrows in Figure 3. At any time, Holders can move or delete data as it remains under their ownership. Encrypted hashes of the data (only a few bytes in size) are held, as shown by the dotted arrow in the upper right of Figure 3, on a blockchain purely to support independent verification. In our design, we use a 'Consortium blockchain', shown in the red circle in Figure 3: this is not a fully public blockchain like Ethereum or Bitcoin, but rather a blockchain shared specifically by a consortium of known providers who have signed up to the Ethics Guidelines we describe in Section 7. This gives us the kind of distributed scalability that increases security, but without the spectre of international public availability that may serve as a disincentive for individuals to participate.

3.3 Data empowerment, trust and security: Solid + Consortium Blockchain

There are two main elements to our infrastructure which facilitate maximal user control and empowerment over their data whilst preserving trust and security. *User data empowerment* is achieved by housing each participant's data within a personal Solid Pod, as mentioned in Section 3.2. Personal data artifacts, such as photos, driving licence or passport numbers and immunity certificates are stored here owned and managed by users.

Trust and security are enabled through a combination of the public/private key infrastructure and the Verifiable Credentials framework described above, coupled with a *consortium* blockchain led by the Open University. A blockchain of this type is a mix of both *Public* and *Private* blockchains. The main difference between a public and a private blockchain is the control: in a public blockchain, no one has supreme authority, while in a private blockchain, there are one or more entities that could potentially have control over other entities. A consortium blockchain introduces the operation of a public blockchain in a semi-private environment. Although such a blockchain is not open for all, the participating entities share equal privileges in creating transactions and building blocks. In this blockchain, at least one entity takes the responsibility of managing the network and approving participating entities, known as nodes, to join the network. A consortium blockchain is most beneficial in a setting where performance, regulatory, or stability considerations make a public blockchain less acceptable to participants [15].

The OU-led Consortium blockchain is a private Ethereum network known as OpenEthereum (formerly Parity Ethereum) [16, 17]. A major difference between the public Ethereum and this

version is the consensus mechanism. Bitcoin and other early blockchains use the slow and ecologically-unfriendly Proof of Work, wherein massive computing power enables nodes to have a better chance of confirming transactions. Recent work in blockchains has focused instead on computationally-light consensus methods [18]. OpenEthereum uses Proof of Authority (wherein several nodes can be in the mutually-agreed privileged position of being allowed to confirm transactions) [19]. For a full-scale rollout, we anticipate being joined by a major IT partner and Pharmacy as well as other universities, appropriate NHS departments, hospitals, and GP practices acting as participating entities in the network.

3.4 How do we ensure privacy?

Several important guidelines concerning privacy were set out by the Sovrin Foundation, a nonprofit organisation with over 70 corporate partners including IBM, CIsco and others, which has the aim of 'driving greater interoperability and a new trust model for securely sharing private information' [20]. We adopt a variation of the three principles set out in the Sovrin.org White Paper [10], in particular modifying their item 2 as shown below in section 3.3.2.

3.3.1. Pairwise-unique DIDs and public keys: "Imagine that when you open a new account with an online merchant, instead of giving them a credit card number or phone number, you gave them a DID created just for them. They could still use this DID to contact you about your order, or to charge you a monthly subscription, but not for anything else. If the merchant suffered a breach and your DID were compromised in any way, you would just cancel it and give them a new one—without affecting any other relationship. The extraordinary consequence of this shift is that a pairwise-pseudonymous DID is not worth stealing." [10]

3.3.2. MEDS/UC: Minimum and Encoded Data Storage / User's Choice: According to [10], **no** private data should be stored on the ledger, even in hashed/encrypted form, to make it future-attack-proof. Sovrin accepts, as do we, the need for pseudonymous identifiers (DIDs), pseudonymous public keys, and agent addresses (e.g. the mobile app endpoints) to be stored in a decentralised ledger, but in addition we offer the user a *choice* regarding whether and where to host personal information (mobile phone, favourite cloud provider, or both), plus the barest minimum for verification purposes, namely *hashes* (irreversible encodings) of private data. This has the following benefits:

- Serves as a user-storage 'vault' for later recovery in case of loss.
- This 'vault' (i.e. the Solid Pod) can reside on the user's phone, or on a favourite cloud provider, or both it is always the user's choice.
- To facilitate later independent verification, it uses a private blockchain with distributed nodes run by a consortium of trusted providers so that there is neither a single point of failure nor a single 'owner' even of the hash of the certificate.
- Even so, it only stores a *hash* on the aforementioned consortium blockchain a non-reversible but provably correct encoding of the certificate rather than the certificate itself

This is a powerful privacy-preserving and tamper-proof approach that we call 'MEDS/UC': Minimum and Encoded Data Storage / User's Choice. Verborgh [21] has a deeper discussion of the nature and importance of these types of emerging paradigm shifts.

3.3.3. Selective disclosure: It is essential that users (certificate Holders) should only have to reveal just the portions of their own personally-held private data that are relevant to specific transactions (e.g. proving that you are over 18 years of age in order to make certain purchases or access certain locations, but without revealing your actual age or date of birth which you prefer to keep private). This is made possible by the technology known as cryptographic zero **knowledge proofs** [22, 23, 24], so named because they provide, to the Verifier who wishes to know, proof of something specific (such as "Age \geq 18"), but with the Verifier having **no** knowledge of any other details, in this case actual age or date of birth. The 'secret sauce' of zero knowledge proofs, as illustrated in [23, 24], is that a mathematical function can be asked to work through a proof of some fact (such as age being greater than X, or the existence of a certain credential), in such a way that the actual steps involved in executing the proof only reach a positive outcome if the fact is true (for example, the positive outcome may require a certain number of steps to execute): so the proof is valid, but still only indirect (e.g. counting steps of execution) without touching the raw data [22, 23]. With these foundations in mind, section 4 describes the characteristics of our app, and Section 5 illustrates the steps involved in the Issuer-Holder-Verifier interactions.

4. COVID-19 Antibody Test Certification: App characteristics

Our 'COVID-19 antibody test certification' (CATC) app builds upon the Verifiable Credentials approach mentioned in section 3, plus our own expertise developed over the past 5 years in the area of blockchain-based certification [25, 26]. The end result combines the following characteristics:

- Wholly resident on the end-user's smartphone, yet usable as an optional augmentation of a plain paper printout (analogous to train e-tickets vs train printed tickets).
- Converts printed output (via next item) from a 'CATC Authority' which could be either the NHS or a trusted provider such as Boots (analogous to the way Boots handles vaccinations).
- One-tap scan of the above printed QR code to store antibody test results.
- One-tap display of CATC evidence on request to show to employer/authority.
- One-tap verification of the above by employer/authority.
- CATC result is owned by the user.
- The app only reveals verifiable CATC results without revealing any personally sensitive information, at the discretion of the user.
- The underlying technology relies on W3C-standard Verifiable Credentials.
- The above innards are hidden: From the user's point of view, it is 'just another app'.

In section 5 we describe a typical transaction life-cycle which embodies the above characteristics.

5. Use case scenario

In the scenario below, we assume that the main 'interested party', i.e. the 'Claims Holder' or 'End User', is someone who wants to get tested for the presence of COVID-19 antibodies, with the hope of obtaining a COVID-19 Antibody Test Certificate. The actions of this person are shown in the middle column of Figure 4. In the leftmost column of Figure 4 we see the actions of the 'Claims Issuer', in this case a trusted pharmacy that is capable of carrying out the required blood test and issuing a certificate with the result of the test, in both paper and digital form. In the rightmost column of Figure 4 we see the actions of the 'Claims Verifier', in this case an employer in a key industry such as an NHS Hospital, keen to re-admit staff back to work after a period of illness. The steps are carried out by the people in the respective roles in the chronological sequence 1-9, and annotated more fully in the explanation further below.



Figure 4. Numbered workflow steps 1-9 in chronological order.

Explanation of numbered steps in Figure 4:

1. Prerequisite/'onboarding' step: Prior to the blood test, certificate issue and verification steps below, we assume that everyone has the necessary COVID-19 Antibody Test Certification mobile app installed and ready to go as follows:

a) Issuer/Pharmacist has downloaded the app, launched it, selected the role of 'Issuer' from an opening menu, entered the location or location code (there will be many 'instances' e.g. many pharmacy locations) and agreed the code which will create the appropriate DID for that Issuer location² (usable on multiple mobile phones).

b) Holder/User has downloaded the app, launched it, selected the role of 'Holder' from an opening menu, and signed up, which will create the appropriate DID for that Holder (which will work on multiple mobile phones for the same Holder)

c) Verifier/Employer has downloaded the app, launched it, and selected the role of 'Verifier' from an opening menu (the Verifier does not require a DID).

2. The Issuer/Pharmacist needs to authenticate that the Holder/User is who they say they are, and thus requests that the Holder/User display both a physical document and a digital document as explained in step 3.

3. The Holder/User presents (a) a physical ID, which is likely to be either a Driving License or a Passport, to be specified by the Pharmacy (this is allowed Physical Evidence as described in Section 5.7 of the Verifiable Credentials Data Model [9]), and (b) a QR code 'QR 1' which is scanned by the Issuer/Pharmacist using the Issuer's mobile phone app. At this point there is a choice of the Issuer (a) tapping to accept the ID, in which case the Holder's photo will be 'burned' into the upcoming steps so that at the final step of verification (step 8 below), there will be no need to display the same physical ID, or (b) leaving the Holder to display the physical ID once again at verification time.

4. The blood test is performed, with results available within approximately 2 hours.

5. Assuming a positive outcome for this example ('Antibodies present above appropriate threshold'), Issuer/Pharmacist prints the result and scans the printout barcode/QR code 'QR 2'.

6. Issuer/Pharmacist taps the app button to generate a digitally-signed test result as a new QR code 'QR 3' for transmission to Holder/User, who in turn scans this new QR code and with one tap digitally counter-signs it as acknowledgement of receipt, creating Holder/User's own 'QR 4'.

7. The Holder/User now has the signed and counter-signed COVID-19 Antibody Test Certificate ready for showing to any Verifier/Employer ('QR 4') — and the paper version from step 5 (not digitally signed) as a fallback.

8. This step is, in many ways, the *raison d'être* for everything this paper is about, i.e. the Holder/User is now able to present a provably valid certificate of immunity to the Verifier/Employer. To avoid someone else impersonating the Holder, the Holder must present

² Our prototype simulates the official Pharmacy registry - enquiries about API access are underway.

not only the certificate, but also some proof of identity. There are several ways to proceed, hence the multiple options shown in the lower part of Figure 4:

- Recall that at Step 3, one option allowed the Holder's ID photo to be 'burned' into the digital certificate so that there would be no need to display the physical ID later on. If that option *had* been taken, then the Holder needs to present only the QR code 'QR 4' created at step 6: when the Verifier/Employer uses the app to scan QR code 'QR 4', the certificate will be verified and the 'burned-in' ID photo of Holder will be displayed for physical inspection.
- If that option had *not* been taken at Step 3, then the physical identity of the Holder can be confirmed by the Verifier by means of visual inspection of a physical ID card, while the Verifier scanning the QR code 'QR' will verify the certificate.
- The physical printout from Step 5 above is also shown in Figure 4 for Step 8, because this is always available as a fallback option in case of mobile phone loss or a specific preference of the Holder or Verifier, particularly during early familiarisation with the digital certificate.

9. The Verifier/Employer's app automatically verifies both signatures and confirms acceptance of the COVID-19 Antibody Test Certificate, at which point the Verifier/Employer can announce a successful result and safely admit the Holder/User, for example, to work.

Time to complete steps 2-9: approximately 3 minutes end-to-end, plus duration of blood test.

6. Behind the scenes: How the scenario works

This section describes the operations that underpin the functioning of the scenario described in Section 5. For simplicity, the processes are divided into three broad categories: *onboarding,* specifying how entities open their accounts and verify their identities; *certification,* explaining how the test is conducted followed by issuing the certificate; and *verification,* describing how the obtained certificates are verified.

6.1 Onboarding

There are three entities involved in the operations: *Issuers*, *Holders* and *Verifiers*. The onboarding process lets all of them install the app and configure. The configuration process for each of them is distinct and requires specific documentation.

Issuers: The onboarding of a potential Issuer (Fig. 5) begins with the person downloading and installing the app. The app then instructs the Issuer to complete an in-app form. The role of the Issuer is sensitive due to the person having the ability to test, validate and issue certificates to individuals. Hence, as a precautionary measure, the app employs *two factor verification* for all potential Issuers. We anticipate using the API provided by the General Pharmaceutical Council, or an equivalent (this is simulated in our prototype — see footnote 2 on page 12) to cross-check the registration and the branch information of the likely Issuer, followed by email verification.

The former requires the person to input appropriate information into the form, while the latter asks the potential Issuer to provide a valid official email address at the company's registered domain name. The app requires the person to tap on a link that it sends to that email address to complete the registration. Data provided by the potential Issuers reside on the phone in Solid Pods.



Figure 5. Issuer onboarding timeline details.

Holders: The process of onboarding Holders (Fig. 6) involves adding an identification document such as a driving license or passport. The document number helps to generate the DID that acts as the anchor for the Holders. A potential Holder first downloads and installs the app followed by adding a photo of the identification document. This document resides in the Solid Pod of the Holder on the phone. Holders may choose to keep a copy on a cloud server of their preference as a backup. This photo document is deemed permanent (but remains on their personal Solid Pod) and once submitted, cannot be changed again. The app then provides the Holder with the DID, leaving the owner of the account ready for testing and certification.



Figure 6. Holder onboarding timeline details.

Verifiers: Amongst three entities, the process of onboarding the Verifiers is the most straightforward. Anyone willing to act as a Verifier can download the app and start verifying. There is no need to create an account for verifying a Holder's certificate. As the Verifier submits no data, the steps of the Verifier onboarding timeline (Fig. 7) do not involve Solid Pods.



Figure 7. Verifier onboarding timeline details.

6.2 Certification

The certification process requires a Holder to visit an Issuer with the exact document used for identification at the time of onboarding. At this point there is a choice: either (a) The Issuer matches this document with the copy stored in the Holder's Solid Pod, viewing it on the app and tapping to accept the ID, in which case the Holder's photo will be 'burned' into the upcoming steps so that at the final step of verification, there will be no need to display the same physical

ID, or (b) simple visual inspection of the physical ID, which means that the Holder will need to display the physical ID once again at verification time. In Figure 8 below, we see the 'behind the scenes' view of certification, including the Holder's Solid Pod with the ID.



Figure 8. Certification: main dataflows.

The app is designed to work in a completely decentralised environment. Its functionalities run across the Issuer's, Holder's and Verifier's phones as well as on the hosting servers, but does *not* have access to the user's data from a central database. Every time the app needs to execute an operation, it reads the data from a particular user's Solid Pod (and only with the user's permission). In Figure 8, at (A) we see that the app reads the data (certificate) from the Holder's Solid Pod, and at (B) compares the certificate's hash with its hash on the blockchain and confirms that on the Issuer's phone display.

Once the identity is confirmed, via physical document checks and Verifiable Credentials demonstrating ownership of the relevant DIDs, the Issuer conducts the immunity test and initiates the process of generating a certificate at (C). A certificate is a set of data in RDF format³ containing the test results and a Verifiable Credential for the Holder's identity of the Holder. While the hash of the certificate goes onto the blockchain at (D), the original document resides in the Solid Pod (E). It is notable that neither the blockchain nor a third party centralised server stores the personal data of the Holder.

³Resource Description Framework: the W3C standard model for data interchange on the Web [27]

The Holder reserves the right to keep a copy of the certificate in a cloud server of his or her choice. In the unlikely event of losing the phone, the Holder can retrieve the data from the cloud and restore the certificate in the regenerated local Solid Pod of the replacement phone. This certificate is visible on the Holder's app in the form of a QR code, giving an easy-to-scan option for Verifiers.

6.3 Verification

The process of verifying a certificate is an on-demand action. A Verifier cannot validate a certificate unless requested. It requires a Holder to go to a Verifier for this purpose. A Verifier can be an employer or other individual or organisation to whom the Holder wants or needs to present the certificate. Figure 9 shows the main data flows involved in Verification, with the explanation overleaf.



Figure 9. Verification: main data flows.

In Figure 9, we see that once requested, at (A), the app reads the QR code from the Holder's phone. This QR code that itself is stored in the Solid Pod of the Holder has two components: The certificate and a URL pointing to the hash on the blockchain. At (B), the app extracts these components and at (C) locally generates a temporary hash of the certificate. Finally (D), the app fetches the hash stored on the blockchain and compares it with the local hash. The matching of the hashes indicates the validity and the authenticity of the certificate stored in the local Solid Pod of the Holder. At the same time, the physical identity of the Holder can be confirmed by the

Verifier by means of visual inspection of a physical ID card, if that is the route the Holder prefers, or alternatively the Holder's photo ID will already be 'burned' into the mobile app certificate because that is the path elected at the time of the Holder interacting with the Issuer, as mentioned above. The digital identity of the Holder can be confirmed by verifying the Verifiable Credential (embedded in the certificate) based on the relevant Holder DID.

6.4 Implementation infrastructure

The components of our implementation communicate with each other via current or in-development Web standards — Hypertext Transfer Protocol Secure (HTTPS), RDF (primarily in the JSON-LD format), Verifiable Credentials, and Decentralised Identifiers — and via blockchain protocols (specifically, Ethereum protocols). The volumes of data and computational requirements are typically small, and can be handled by a mobile device (full blockchain nodes are an exception, due to the potential size of the full chain data).



Figure 10. Overall Implementation Architecture.

The main software functions required by the implementation are as follows, and represented as lozenges in Figure 10::

Generate QR codes: Implemented using standard libraries on a mobile phone to generate QR codes for identity and immunity certificates.

Generate hashes: Implemented using standard libraries on a mobile phone. Certificates are transformed into a canonical RDF format before hashing, in order to ensure robust reproducibility of hashes, for verification.

Communicate with Blockchain: The Parity library is used to communicate with our Consortium Blockchain. A light client library can handle read/write interactions with the blockchain without requiring a phone to maintain a full copy of the blockchain. This is shown using the thin dotted lines in Figure 10.

Communicate with Solid Pods: Communication with Solid takes place using the Solid REST API [28], to read and write personal data regarding the Holder to and from their Solid Pod with user permission. This is shown in thick dotted lines in Figure 10, just for a few cases (one between the mobile app in the upper right and a cloud hosted Solid Pod; one between the locally hosted Solid Pod on the left and that same cloud hosted Solid Pod; one between the locally hosted Solid Pod on the left and the locally hosted Solid Pod on the right).

Manage Issuer and Holder Credentials: Issuer and Holder credentials are stored in public/private key wallets containing DIDs. The authorisation for an Issuer to create certificates can be represented as a Verifiable Credential issued by the relevant regulatory authority to the Issuer, which any participating party can verify. Currently we use Streetcred ID [29] to generate DIDs for the Issuers, Holders and Certificates.

Generate Verifiable Credentials: Certificates are created at issue time, and their contents asserted as the Claim elements in Verifiable Credentials to be stored in the Holder's Solid Pod, with metadata describing the relevant blockchain records forming the Proof. This provides a sharable data structure which permits anyone to check its authenticity.

The mobile app

The mobile app can provide all the necessary UI elements for the Issuer, Holder and Verifier to perform their actions. At the time of writing, the main functionalities of the mobile application include the ability to scan and generate QR codes and generate hashes for text and images. For the QR code scan and generate functions to work, the mobile app is packed with necessary libraries to support QR code functions and only works on smartphones with built-in camera

functionality. The mobile app also contains the hashing libraries. As the mobile app needs to communicate with a server, an active internet connection is necessary for HTTPS server calls.

For speed of implementation for the current prototype, a Node.js Express server does all the heavy lifting functions for the mobile app, with the functionalities explained above. This is a temporary solution, however, given the urgency of the current situation.

7. Ethical considerations

New technologies bring new challenges for society. In the context of the Coronavirus Pandemic of 2019/2020, there is growing activity underway on a strand of work orthogonal to ours known as 'contact tracing', intended to help with COVID-19 detection and prevention. An alliance between Apple and Google to embed interoperable encrypted tracing technology deep into their iOS and Android operating systems for precisely this purpose was announced on 10th April 2020 [30]. Alarms have already been raised about the dangers of such technology, for example by the American Civil Liberties Union [31], despite assertions that the technology takes unprecedented steps to encrypt personally identifiable information.

With respect to the proposals in this paper, commentators have argued (e.g. in a compelling Guardian editorial about the dangers of Immunity Passports [5]), that certification of the type we have envisaged would entail multiple risks. In particular, such commentators claim, the approach that we have developed in the previous sections could, in the worst case scenario:

- Disenfranchise the poor and others who do not have access to the technology or the tests.
- Create a two-tiered 'have/have-not' society with extra privileges available for those in the 'have' position, i.e. those who have the digital certificate of immunity.
- Be a stepping-stone for other future governments, in the UK or elsewhere, to deploy the same concept either to enable or to enforce discrimination based on other acquired or inherited characteristics, whether health-related or arbitrary other conditions.
- Potentially motivate the 'have-nots' to 'acquire the certificate or even the disease' somehow, for example if not by forgery, then by deliberately getting the disease in the hope of getting back to work sooner.

We take these objections seriously, and have saved this section for the end so that the particular steps we are taking to ensure privacy had an airing first. It should be clear from the previous sections that the concepts underlying Verifiable Credentials (section 3.1) and Decentralised Verification of Data with Confidentiality (section 3.2) are diametrically opposed to any kind of central data storage or 'Big Brother'-style snooping and data collection, and indeed provide excellent and agreed standards for avoiding such snooping and data collection. We need to state this again, in no uncertain terms: in the approach advocated in this White Paper,

Personally identifiable information is stored entirely under the Holder's control (on a mobile phone, on the Holder's cloud provider of choice, or both), and additionally for later verification purposes in minimal (a few bytes) encoded form (hash) on a consortium blockchain. Moreover, the app allows the user selectively to present *only* the specific test result, with no other personal information revealed.

Additional strong ethics guidelines are suggested below.

How is it possible that no personal information is stored in a database? What about the certificate itself? That's the beauty of Verifiable Credentials, Zero Knowledge Proofs and our approach of 'MEDS/UC' — Minimum and Encoded Data Storage / User's Choice: Taken together, this combined approach offers cryptographically signed, verifiable, untamperable proof that the certificate being shown was really granted by a known testing authority to the person in question, even without showing the name, address, phone number or even NHS number of the person holding it. This approach might feel a little unfamiliar to Holders/Users at first, and thus paper certificates are likely to be carried by certificate Holders/Users at the same time until 'comfort levels' have improved, as in our proposed opt-in guidelines below.

To drive home the point about our concern for privacy, we have an important observation for those who might fear falling under government surveillance for a significantly long time. Our app abolishes the basis for that fear. Everything in this app is decentralised. Anyone wishing to abandon involvement in this kind of certification can just delete the Verifiable Credentials stored on their Solid Pods. There will be no records whatsoever, as if they were never on the system. Deleting data on the Solid Pods will also turn the hashes on the blockchain into 'orphans' (no data pointing to the hash), i.e. the hashes will become meaningless: it is not possible to recover the original data from a hash.

This almost-too-good-to-be-true approach does raise a fresh concern: the same techniques we are advocating seem to open up what we call the '*Private Verifiable Credentials Paradox*': your digital mobile app certificate is so much more private and tamper-proof and 'un-snoopable' than the old paper or database versions that it can inadvertently, in the eyes of the critics, serve as a powerful 'Self-Sovereign Passport' that can be (deliberately or accidentally) weaponised *for discrimation against your fellow citizens*. At this point the critics appear to have wrapped us in a rhetorical double-bind: the technology, say the critics, is either too *imperfect* (and therefore, by sacrificing your privacy, can be used against you), or else it is too *perfect* (and therefore, by allowing you to be flagged as 'safe', can be weaponised for use against your fellow citizens). We have dealt with the 'too imperfect' criticism above by means of our approach to Verifiable Credentials and decentralised verification of data with confidentiality, as provided in great detail. Below, we turn our attention to the 'too perfect' (weaponised) criticism.

History is full of the tragic use and abuse of certificates and other documents or symbols to enforce discrimination and even genocide, without neccessarily requiring high-tech methods to achieve such a sorry state of affairs (although the better the technology, the greater the danger: see Christopher Allen's slide show [32] for a chilling account of how the award-winning Identity Card Registry for the Netherlands in 1936 went badly wrong when it fell into the wrong hands, thereby providing one of the strongest possible arguments against centralised data bases — the opposite of the decentralised approach advocated herein). These may be extreme examples, but worst-case scenarios are precisely what ethical considerations should rightly address. Clearly, the more powerful methods of today and tomorrow have the potential to open up a Pandora's Box of Bad Use, if not by the modern democracies in which we may have grown up, then by some authority in another time or another place. We started this project with the noble aim of facilitating the 'pandemic end game': a way to start getting people back to work and heading towards recovery from the devastating impact of the Coronavirus Pandemic of 2019/2020. If COVID-19 antibodies can indeed be shown reliably to confer immunity, and the overwhelming support for the 'test-test' mantra of the World Health Organization continues to hold, then people are going to get tested, in overwhelming numbers, and certificates are going to be issued in one form or another.

But we are not adopting a 'give-up-and-accept-our-fate-in-the-hands-of-bad-actors' approach. Yes, a secure digital certificate could hypothetically be weaponised to a greater degree than a paper one, but the actual degree could be something of a mind-set illusion. *Any* certification method has such potential, and therefore rather than casting the technology in terms of 'good vs evil' we think our approach is best considered as something that involves a trade-off between (a) the advantages of getting people back to work using good privacy-preserving fraud-prevention methods and (b) the disadvantages of discriminatory (mis)use of such methods. Our approach to this trade-off is strongly to nudge things towards (a), and therefore we propose the following concrete steps to achieve this:

- App usage should be strictly opt-in/optional: a paper certificate must always be allowed by default, just as with, say, train and airline tickets. This helps introduce the concept and technology in a gentle manner: people will ultimately decide what they prefer for themselves.
- Implementations must comply with NHS Information Governance (IG) guidelines [33, 34]. Compliance should in principle be straightforward, because (a) in our approach, Personally identifiable information is stored entirely under the Holder's control (on a mobile phone, on the Holder's cloud provider of choice, or both), and additionally for later verification purposes in minimal (a few bytes) encoded form (hash) on a consortium blockchain, and (b) the app allows the user selectively to present only the specific test result, with no other personal information revealed. Even so, the NHS IG documents provide a strong guiding framework for ensuring continuing compliance, particularly with respect to relevant GDPR requirements such as 'Right to erasure' and 'Right to data portability': our architecture by its very design avoids database storage of personally

identifiable information, but oversight of possible misuse/abuse of this and related technologies needs to be maintained, as the next three bullet points suggest.

- COVID-19 Antibody Test Certificates should *only* be applied to workers in healthcare and other comparable key sectors, as defined by the appropriate Parliamentary process (for example, the list of key exceptions to mandatory business closure during the current pandemic was specified by the Ministry of Housing, Communities, and Local Government), with input from an Ethics Committee mentioned next.
- An Ethics Committee, comparable in scope and composition to the NHS Research Ethics Committees, should have oversight of actual deployment of the approach advocated herein.
- The approach should be reviewed on a 3-monthly basis.

Ethical standards are a challenge to uphold, but uphold them we must, as we see this as the best way to negotiate a path towards a 'pandemic end game' in a manner acceptable to the widest possible audience.

8. Conclusions

The perceived need for a COVID-19 Antibody Test Certificate (CATC), particularly for healthcare workers and others in key industries, and particularly if shown to be biologically robust, has motivated us to develop a mobile app based around Verifiable Credentials, distributed storage of cryptographic public/key pairs, and the decentralised verification of data with confidentiality. This has enabled us to provide a facility that is 'just another app' from the viewpoint of the end-user (the 'Holder'), healthcare professionals (the 'Issuer'), and employers and other relevant authorities ('Verifiers') — thereby providing a tamper-proof record owned entirely by the end-user, yet allowing the end-user to selectively reveal just the proof of the test results without surrendering other personal information, and requiring only mobile app downloads from everyone in the loop. This app and its secure digital certificate together become a powerful adjunct/enhancement to traditional paper-based certification from the NHS or Pharmaceutical testing authority, no more onerous than train e-tickets as an adjunct/enhancement to train ticket printouts — and without the need for costly installation of special 'e-ticket reader' hardware: a CATC app is sufficient for the task at hand, regardless of which of the three roles is involved.

Will such an app be suitable as part of a 'pandemic exit strategy' for helping get people back to work in key sectors? There are a lot of issues to be addressed first, including the rigorous testing and approval of antibody tests, agreement concerning ethical oversight and acceptance by the public. Our approach is intended to ensure that the procedures for creating tamper-proof, verifiable, privacy-preserving certificates are 'ready to go' while waiting for antibody/immunity tests to achieve the required state of robustness and acceptance. We believe that, just as with train e-tickets, end-users will 'vote with their feet' and deploy the app in large numbers once its benefits have been demonstrated. To take a stance against what we call the 'Pandora's Box of Bad Use', we proposed ethical guidelines at the end of Section 7, which we

believe are essential for the principled development and deployment of the prototype described in this paper.

WORK WITH US: Please contact us at kmi-director@open.ac.uk if you would like to be involved in this work. We know that the security of a decentralised ledger increases as the number of nodes increases. Thus, there is a need for other academic institutions in particular to be willing to set up full nodes and issue DIDs, for which we can provide open source code and instructions.

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