One-Shot Signatures and Applications to Hybrid Quantum/Classical Authentication

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ABSTRACT

We define the notion of *one-shot signatures*, which are signatures where any secret key can be used to sign only a single message, and then self-destructs. While such signatures are of course impossible classically, we construct one-shot signatures using *quantum no-cloning*. In particular, we show that such signatures exist relative to a classical oracle, which we can then heuristically obfuscate using known indistinguishability obfuscation schemes.

We show that one-shot signatures have numerous applications for hybrid quantum/classical cryptographic tasks, where all communication is required to be classical, but local quantum operations are allowed. Applications include one-time signature tokens, quantum money with classical communication, decentralized blockchain-less cryptocurrency, signature schemes with unclonable secret keys, non-interactive certifiable min-entropy, and more. We thus position one-shot signatures as a powerful new building block for novel quantum cryptographic protocols.

CCS CONCEPTS

• **Security and privacy** → **Digital signatures**; • **Theory of computation** → **Cryptographic primitives**; **Cryptographic protocols**; • **Hardware** → **Quantum communication and cryptography**.

KEYWORDS

One-Shot Signatures, Quantum Money, Hybrid Quantum Cryptography

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1 INTRODUCTION

Quantum computing and quantum information promise to reshape the cryptographic landscape. In the near term, quantum computers will be able to break much of the cryptography currently used today [40], with the field of *post-quantum cryptography* developing new alternative protocols. On the other hand, *quantum cryptography* will leverage quantum communication to open new possibilities such as information-theoretically secure key agreement [11], physically unclonable money [43], and more.

Yet, even in a world full of quantum computers, classical cryptosystems and communication will still play a fundamental role. The unclonability of quantum data, for example, means that tasks such as backing up a quantum hard drive or forwarding a quantum email (while still keeping the original) will be impossible. Even in a world where quantum computing is commonplace, it may be infeasible to run a quantum computer in many computing environments, such as mobile or embedded devices. It may also be some time before our communication infrastructure is updated to support the transfer of quantum data; besides, most data users will care about is still classical, so it may seem as overkill to use quantum information to send such data. With classical communication, however, most of the exciting developments from quantum cryptography become unusable. This then leads to the following natural question:

When exchanging only classical information, can local quantum computing still offer advantages over purely classical systems.

In some cases, the answer is certainly negative. For example, information-theoretic key agreement [11] is impossible with classical communication, even if local quantum operations are allowed. Indeed, in quantum key distribution, security is only obtained because the honest parties can detect if the adversary is eavesdropping; on the other hand, with classical communication, the adversary can listen to the communication undetected. Another related example is information-theoretic key recycling [19, 25, 38].

Hybrid quantum/classical cryptography. On the other hand, in an emerging field that we will call *hybrid quantum/classical cryptography* — or *hybrid quantum cryptography* for short — it has been shown that local quantum operations *can* yield an advantage in some settings. Recent work has shown how to attain *certifiable randomness expansion* [12], which enables a classical client, for whom generating true randomness is a notoriously difficult task,

to verifiably outsource the generation of random bits to a quantum computer, which can generate random bits easily. This task is closely related to the goal of *quantum supremacy* — demonstrating that quantum computers can solve certain problems faster than classical computers — which has recently gained much attention. Certifiable randomness has also been extended to certifying arbitrary outsourced quantum operations, again using only a classical client [33].

Given the importance of classical communication in a quantum world, we anticipate such hybrid protocols to complement post-quantum and quantum cryptography and become a third pillar of active research at the intersection of cryptography and quantum computing. Our goal in this work is therefore to provide new foundational tools for this emerging area and develop novel applications.

1.1 Motivating Example: Signature Tokens

Consider the task of signature delegation: Alice wishes to allow Bob to sign a single message on her behalf. Alice could just give Bob her secret key, but this would allow Bob to sign any number of messages. Alice instead wants to give Bob enough information to ensure that Bob can subsequently sign a single arbitrary message, without any further action on Alice's part. Crucially, we want the message to only be decided *after* Alice hands this information to Bob.

Of course, this task is impossible in a purely classical world, as Bob can re-use whatever information he learned from Alice to sign any number of messages. One could hope that Alice could provide Bob with a *quantum* signing token, which self-destructs after signing a message. By quantum no-cloning — which says that general unknown quantum states cannot be copied — Bob cannot copy the token, and therefore can only sign a single message. Indeed, Ben-David and Sattath [10] show that such quantum signing tokens are possible by building on ideas for public key quantum money [2].

No-cloning with only classical communication? But what if we insist on classical communication between Alice and Bob[1]? How can we leverage the power of no-cloning, when any information Alice sends to Bob can be copied unrestrictedly? It would seem that if Bob can derive a signing token from their communication, he can simply copy the communication transcript to derive as many distinct signing tokens as he would like.

The issue is actually very general, and is potentially problematic in any hybrid quantum protocol. After all, quantum no-cloning and related concepts can be seen as the foundation for essentially all of the novel features in quantum protocols. But now, what if we insist on only classical communication, relegating all quantum operations to local computation? This means that any application of no-cloning applies to states *that the adversary constructed entirely on his own*. How can we guarantee no-cloning, if the adversary controls the entire process used to generate the state in the first place? Why can't the adversary just run the same process twice, generating two copies?

Perhaps surprisingly, we will demonstrate that with a single *classical* back-and-forth between Alice and Bob, Alice can send Bob a single-use quantum signature token. In doing so, we demonstrate how to overcome the difficulty outlined above and leverage no-cloning in a setting where all communication is classical.

A Toy Example. How is this possible? To illustrate how classical communication might be combined with local no-cloning, we recall a basic scenario described by Zhandry [45], which also underlies the recent developments in certifiable randomness/quantum computation [12, 33]. Let H be a many-to-one hash function that is collision-resistant against quantum attacks. First, generate a uniform superposition of inputs. Next, compute the hash H in superposition and measure the result, obtaining a value y. The original state collapses to the superposition $|\psi_y\rangle$ of all pre-images x of y.

Using the above procedure, it is easy to sample states $|\psi_y\rangle$. However, at the same time it is impossible to sample two copies of the same $|\psi_y\rangle$, assuming the collision-resistance of H. Indeed, assume toward contradiction that it were possible to generate two identical copies of $|\psi_y\rangle$. Then simply measure both copies; each measurement will likely yield a different x, resulting in two distinct values mapping to the same y, a contradiction.

A First Attempt. As a first attempt at a signature delegation protocol, we have Bob sample a pair $(|\psi_y\rangle, y)$, and send the classical value y to Alice. Alice then signs y using some standard post-quantum signature scheme, sending the resulting signature σ back to Bob. The result is that, with only classical communication between Alice and Bob, Bob has arrived at a value $(|\psi_y\rangle, y, \sigma)$ that he cannot clone (due to the collision resistance of H), nor can he sample on his own (due to needing Alice's signature on y).

Of course, we have to also describe how $(|\psi_y\rangle, y, \sigma)$ can be used to sign a single message, but not two. For general hash functions H, there is likely no meaningful way to accomplish this. For example, if the hash function is *collapsing* [41], then having $|\psi_y\rangle$ is essentially no more useful than having a single classical pre-image x. But of course a classical pre-image x cannot be used as a one-time signing token, since it can be copied. Recent evidence suggests that typical post-quantum hash functions are likely collapsing [32, 41].

Toward a solution, we observe that our protocol so far bears resemblance to the chameleon signatures of Krawczyk and Rabin [30]. Here, H is replaced with a special type of hash function, called a *chameleon hash*. In such a hash function, Bob knows a trapdoor T which allows him to "open" the hash y to any message m' of his choosing. In particular, given y and *any* message m', Bob can find an r' such that $H(m', r') = y$.

We immediately see that chameleon hashing provides a partial solution to signature tokens. Indeed, Bob can choose the hashing key H together with a secret trapdoor T, and send Alice any hash y, which Alice then signs using her signing key. To sign a message m, Bob can then use the trapdoor to open y to any message m, computing an r such that $H(m, r) = y$. Finally, Bob can then output (m, r, y, σ) as the signature on m. The recipient will verify Alice's signature on y and that $H(m, r) = y$.

This certainly works for delegating signatures. It is also mimics how signing authority is delegated in practice, where instead of signing a hash, Alice would sign the a public key for Bob's signature scheme. But this standard delegation mechanism of course cannot provide the one-time property we are looking for, as it is purely classical. Indeed, unforgeability relies on the collision resistance of

[1] We will not even allow shared entanglement, which could be used in teleportation.

H, which means Bob can break unforgeability using his trapdoor. In particular, Bob can re-use his trapdoor as many times as he wishes, opening y to any number of messages of his choice.

Our Solution: one-shot chameleon hashing. To remedy this issue, we imagine that Bob has a variant of chameleon hash functions, where any given trapdoor can be used only a single time. Specifically, we want that the hash function remains collision resistant *even to Bob*. In more detail, we define a *one-shot chameleon hash function* as a hash function H with the following property: it is possible to first sample a hash y together with a *one-time quantum* trapdoor $|T\rangle$. Then, after seeing a message m, it is possible to use the trapdoor $|T\rangle$ to sample r such that $H(m,r) = y$. Importantly, *anyone* can sample a $y, |T\rangle$ pair, and H is collision resistant to *everyone*. This implies that once $|T\rangle$ is used to compute r, it must self-destruct, preventing further openings. This in particular implies that $|T\rangle$ cannot be classical, else it could be copied as many times as Bob would like.

Notice that all communication — namely y and σ — is classical. We also stress that we want H to be a classical function. As such, Bob's quantum operations are entirely local. What's more, Bob is the *only* party that is running a quantum computer; Alice can be purely classical.

Generalization: one-shot signatures. We can even abstract the protocol above slightly, to work with a more general object called *one-shot signatures*. Here, anyone with a quantum computer can sample a *classical* public key pk, together with *quantum* secret key $|\mathsf{sk}\rangle$. Given $|\mathsf{sk}\rangle$ and a message m, it is possible to compute a classical signature r on m. Then anyone, knowing just the public key, can verify signatures. For security, we require that it is infeasible to compute a tuple $(\mathsf{pk}, m_0, r_0, m_1, r_1)$ such that $m_0 \neq m_1$, and r_0 and r_1 are valid signatures of m_0, m_1 respectively, with respect to the public key pk. We see that one-shot chameleon hashing is just a special case of one-shot signatures where verification simply evaluates $H(m,r)$, and checks that the result is pk.

At this point, it should be unobvious that one-shot signatures can even exist. After all, one-shot signatures can be seen as an extremely strong variant of the quantum no-cloning theorem. The original no-cloning theorem dealt with truly unknown quantum states, which were useless to anyone who did not know the states, and therefore for whom no-cloning applied. Public key quantum money [1] can be seen as a strengthening, where no-cloning still holds even for parties that have the ability to verify the state. Even this verifiable version of no-cloning has been notoriously difficult to achieve. Quantum lightning is then a further strengthening, where no-cloning holds even for parties that devised the original state themselves; the only existing construction is that of Zhandry [45], which is based on new ad hoc hardness assumptions.

One-shot signatures can then be interpreted as yet a further strengthening of quantum lightning where the un-clonable state has been endowed with the ability to sign a message. Given the difficulty in even achieving the weaker forms of no-cloning, it is natural to wonder whether one-shot signatures are even possible.

1.2 Our Results

In this work, we explore applications similar to the above, where local quantum operations yield surprising new protocols with classical communication. Our central building blocks will be one-shot signatures and one-shot chameleon hash functions. Our results are as follows:

One-shot signatures and one-shot chameleon hash functions (Sections 2,3,4). As our first contribution, we give formal definitions for one-shot signatures and one-shot chameleon hashing.

We also construct one-shot chameleon hashing, and hence one-shot signatures. We observe that prior work essentially constructs this object [5], but only relative to a quantum oracle, and there is no known way to instantiate the oracle. We improve on this by demonstrating a *classical* oracle (but query-able in superposition) relative to which we can build one-shot chameleon hashing and signatures. Even finding a plausible classical oracle to build one-shot chameleon hashing exists is highly non-trivial. Our main idea is to start from a hash function which is periodic. Such a function is certainly not collision resistant against quantum attacks due to quantum period finding, but at least it is straightforward to show that it gives rise to the chameleon property we need. We then recursively divide the set of pre-images of each output into another periodic function. Importantly, we choose different periods for each set of pre-images to avoid the overall function becoming periodic. In fact, we perform this recursive division several times, each time using a different period for each set of pre-images. We demonstrate that this recursive structure nevertheless preserves the chameleon property. We prove that our one-shot chameleon hashing is collision resistant relative to this oracle using a modification of the polynomial method. Our classical oracle can then heuristically be obfuscated using post-quantum *indistinguishability obfuscation* (e.g. [7]) to yield a plausible construction in the common reference string model.

Signature delegation. We then turn to applications. Many of our applications can be seen as applications of our signature delegation mechanism above. We demonstrate that our signature delegation protocol works, and can easily be delegated multiple times, with Bob delegating to Charlie, who delegates to Dana, etc. The overall signature is the entire signature chain from Alice to the final signer.

Budget Signatures (Section 4). We can also delegate to *pairs* of public keys. Such delegation allows us, for example, to construct *budget signatures*. Here, when signing a message, we specify a *budget* $b > 0$. Each public key will come with a total budget B, and the security property is that Bob can sign any number of messages, so long as the total budget remains less than B.

In our scheme, the public key for a total budget B will simply be the pair (pk, B) where pk is the public key for a one-shot signature. To sign a message m with budget b at most the total budget B, simply sign m using the one-shot secret key, using up the secret key. Alternatively, one can delegate to two budget signature public keys $\mathsf{pk}_0, \mathsf{pk}_1$ with budgets B_0, B_1 respectively, where $B_0 + B_1 \leq B$. To do so, simply sign the concatenation of the two public keys. Those budget signatures can then be recursively used to sign with budgets B_0, B_1. When verifying the signature relative to pk_0, additionally verify the signature on $\mathsf{pk}_0, \mathsf{pk}_1$ relative to pk, as well as that $B_0 +$

$B_1 \leq B$. Since we know pk_0 can only sign with budget up to B_0 and pk_1 can only sign with budget up to B_1, this verification guarantees pk can only sign with budget total budget up to $B_0 + B_1 \leq B$. In typical usage, we imagine that to sign a message with budget b, we will first invoke this delegation with $B_0 = b$ and $B_1 = B - b$, and then sign m with respect to pk_0, using the secret key in the process. Further messages are signed with respect to pk_1.

Quantum money with classical communication (Section 5). One-shot signatures readily yield public key quantum money, where the mint has a public key that allows anyone to verify. Basically, the quantum signing key $|\mathsf{sk}\rangle$ for a one-shot signature serves as the quantum money state.

Using our signature delegation mechanism, we show how to send quantum money using only *classical* messages. The mint's public key will be the public key for a classical post-quantum signature scheme. To mint a banknote with value V, the mint simply creates a secret key/public key pair $(|\mathsf{sk}\rangle, \mathsf{pk})$ for a one-shot signature scheme, and signs the pair (pk, V) using it's classical signature scheme to get signature σ. Sending the note to someone simply invokes our delegation procedure. By combining with our budget signatures, our quantum money scheme is also infinitely divisible, unlike existing constructions.

Decentralized blockchain-less cryptocurrency (Section 5.2). One-shot signatures also immediately give rise to quantum lightning, yielding the first construction with provable security relative to a classical oracle. As explained by Zhandry [45], by combining with a suitable proof of work, quantum lightning gives a decentralized cryptocurrency, where the double-spend problem is solved using no-cloning as opposed to a blockchain. Zhandry's scheme, however, requires quantum communication.

We combine our delegation scheme with proofs of work to give blockchain-less cryptocurrency using only *classical* communication. The basic idea is that, to mint a new note, the miner generates a secret key/public key pair for a one-shot signature scheme. Then the miner uses the public key as the challenge in a proof of work. The completed proof of work and the key pair constitute the note. Spending the note just involves our delegation mechanism, except that for the first transaction, the miner appends the proof of work to the message he signs. This construction can be seen also to offer the first embodiment of a "reusable proof of work" [23] that does not rely on a hardware assumption.

Ordered Signatures (Section 6). Here, when signing a message, one also specifies a tag t. The signing key allows for signing any message, but the requirement is that messages can only be signed in order of increasing t. That is, once a message is signed at tag t_0, it then becomes impossible to sign a message at a "past" tag $t_1 < t_0$.

Our construction is very simple: the public key will be the public key for a one-shot signature scheme. To sign a message at tag t, simply construct a new one-shot signature public key/secret key pair $(\mathsf{pk}, |\mathsf{sk}\rangle)$, and delegate to the new public key. When signing to delegate, sign the entire public key/tag/message triple. $|\mathsf{sk}\rangle$ becomes the new secret key, and the signature consists of the entire signature chain from the original public key to the latest public key. To verify, simply verify the signature chain, as well as verify that the tags in the chain occur in increasing order. The idea is that, by the one-shot security of our signatures, the only way to produce a new signature is to append to the signature chain. Therefore, once an adversary produces a signature at tag t_0, he has committed to all the signatures he will produce at tags $t_1 < t_0$. If he tries to sign a different message at t_1, this will constitute a fork in the chain, violating the one-shot security property.

Ordered signatures allow one to provably destroy their signing key by signing a dummy message at time ∞. Or one can at provably update their key by dividing time into epochs, and signing a dummy message at the end of an epoch to update to the next epoch.

Key-Evolving Signatures and Proof-of-Stake based Blockchains (Section 6.1). Ordered signatures provide a first instantiation of key-evolving signatures in the erasure model. A key-evolving signature (KES), (see e.g., [24]) enables key updates at regular intervals (or per message) so that a key exposure incident at a certain time cannot compromise the unforgeability of past periods. Instantiating KES classically is only possible assuming erasures, i.e., that the party is capable of erasing its old private state after the update. Applying ordered it is possible to obtain a KES in the non-erasure model, i.e., the setting where the adversary may have access to past states.

This observation circumvents a standard model impossibility result and solves an open question in Proof-of-Stake (PoS) blockchain protocols, [6, 14], regarding their security in the non-erasure model: in these protocols, in order to solve the problem of "long range attacks" (see e.g., [13, 27]). key-evolving signatures are utilized to ensure that corruption of past keys cannot provide any advantage to an attacker that corrupts old keys that used to be associated with a large percentage of stake but have since been depleted. In the classical non-erasure model such corruption leads to a long range attack that can break consistency (see e.g., [18] where this is stated as a formal impossibility). Basing the proof-of-stake operation on an ordered signature eliminates this attack vector and facilitates a secure PoS blockchain in the non-erasure model.

Single-signer Signatures (Section 6.2). Here, the secret key is subject to quantum no-cloning, meaning that at any time, only a single user is capable of signing with respect to a given public key. Our ordered signatures readily give such single-signer signatures, by simply having the tag t be a counter, incremented with each signature. Security is proved as follows: toward contradiction, if one *could* split a secret key into two states such that each state is independently capable of signing, then it is impossible to guarantee any order between the signatures produced by each state, breaking the underlying ordered signature.

Of course, this signing capability can be transferred by sending over the quantum secret key; our signatures can also easily be transferred with only classical communication, again using our delegation mechanism.

We observe that single-signer signatures can be seen as yet a further strengthening of quantum no-cloning. Whereas one-shot signatures endow the unclonable state with the functionality of signing messages, the functionality can only be used a single time before the state self-destructs. Single-signer signatures instead give the unclonable state the perpetual ability to sign an unlimited number of messages, but this ability cannot be split amongst two parties.

Delay Signatures (Section 6.3). Adding proofs of sequential work (PoSW) to our ordered signature construction, we obtain what we call *delay signatures*, where the signer must wait a certain amount of time between signing messages.

As a potential application we imagine combining delay signatures with our quantum money scheme. The result is that the mint can only mint new currency at a certain rate. This would prevent an untrusted government from paying debts by simply minting unlimited money.

Proofs of quantumness (Section 7.1). One-shot signatures easily give rise to a proof of quantumness: to prove quantumness, generate a public key for a one-shot signature scheme, and send it to the verifier. The verifier then chooses and sends back a random message. Respond with a signature on the message. A simple rewinding argument shows that any classical adversary that passes verification can be used to sign two messages with respect to the same public key, violating one-shot security.

Interestingly, our proofs of quantumnes are public coin, meaning soundness holds even if the verifier's random coins are public. Such protocols can be made *non-interactive* using the Fiat-Shamir heuristic. Prior protocols [12] are interactive and secret coin, and there is no obvious way to turn them into non-interactive protocols.

Certifiable Randomness (Section 7.2). Our proofs of quantumness also immediately give rise certifiable min-entropy, which is again public coin and can be made non-interactive with Fiat-Shamir. Again, prior protocols required multiple rounds[2].

1.3 Related Literature

Comparing our primitives with classical primitives. Most of the cryptographic notions in this work can be thought of as "one-shot" versions of existing classical cryptographic primitives. One-shot chameleon hash functions generalize the classic equivalent introduced by Krawczyk and Rabin [30]. Our one-shot signatures are the one-shot analogue of one-time signatures by Lamport [31] in the sense that one not only is unwilling to generate a second signature but also he is unable to. Our chain of delegations, our quantum money scheme and our ordered signatures use components from the Naor-Yung paradigm for building full-blown signatures out of one-time signatures [37] and our budget signatures shares similarities with Merkle signatures [35].

Quantum Query Complexity. Our query complexity lower bound uses elements from Ambainis's adversary method [4], as well as techniques for building public-key quantum money by Aaronson and Christiano [2] and tokens for digital signatures by Ben-David and Sattath [10]. Our construction of equivocal hash functions relative to a classical oracle extends the *pick-one* trick by Ambainis et al. [5] and implies the existence of quantum lightning by Zhandry [45]. Interestingly, unlike previous results, our collision resistance lower bound is not based on the polynomial method [8]. The polynomial method works well in proving indistinguishability between oracles but little can be done when it comes to search problems. Indeed, proving that a function is collision resistant through indistinguishability from injective functions immediately implies that it is collapsing!

Collapsing Hash Functions. The construction of equivocal hash functions from standard assumptions is a highly non-trivial task as shown by a line of works. Unruh [42] introduced the notion of collapsing hash functions and proved that the random oracle is collapsing. Since then, several works have proven that numerous collision resistant hash functions from standard assumptions are collapsing [17, 32, 41] and thus not equivocal.

Cryptocurrencies. Our decentralized cryptocurrency construction and its extensions share similarities with blockchain constructions such as Bitcoin's mining using proof of work [36] as well as Ethereum's concept of smart contracts [44]. Mining in the quantum world has also gained attention in the recent years. Although Grover's algorithm can be used to obtain a quadratic speed-up over classical computers for the problem of finding pre-images that map to small hashes in the random oracle model (see e.g., [15]), Aggarwal et al. [3] have proven that there exist hash-functions with smaller than quadratic speed-up.

Quantum Money. Quantum money, first introduced by Wiesner [43], has received a lot of attention the past decade with numerous results in the secret-key setting, where the bank must be involved in verification. Gavinsky [26] has proven that quantum money where the coins are minimally entangled is possible in this setting. Radian and Sattath [39] recently created a secret key quantum money scheme where the minting algorithm is also classical; they called this notion semi-quantum money. However, for their protocol, spending the money still involves sending a quantum state, and verification requires the mint. Farhi et al. [21] have shown that public-key quantum money where the verification is a projective measurement onto a 1-dimensional subspace is impossible without high entanglement. As a result, since one-shot signatures imply such a quantum money definition, secret keys have to be highly entangled.

One-time Memories. Signature delegation can be thought of as the authentication analogue of decryption delegation, known in the literature as *one-time memories*, introduced by Goldwasser et al. [28]. These are memories that allow one to extract a single secret out of them. Unlike signature delegation, one-time memories are impossible even in the quantum world, and even relative to a (quantum) oracle. This is because extraction is a deterministic process and, hence, the *information-disturbance tradeoff* principle implies that such an extraction does not collapse a quantum state.

Proof of Quantumness. Private coin proofs of quantumness out of standard post-quantum assumptions have already been proposed in the literature. Brakerski et al. [12] have proven that under the LWE assumption, there is a private coin interactive protocol for proof of quantumness.

Multi-device protocols. As a precursor to the more recent hybrid quantum protocols, Colbeck [16] proposed a setting where a classical experimenter interacts with *multiple* potentially untrustworthy quantum devices, with the guarantee that the devices cannot communicate. As in our protocols, all interaction is classical.

[2]Though the prior protocols are able to achieve (statistically close to) uniform randomness. In contrast, as explained by Zhandry [45], any non-interactive protocol can never achieve uniform randomness. Our protocol achieves super-logarithmic min-entropy.

However, Colbeck's protocol, in addition to requiring multiple non-communicating devices, inherently relies on the quantum devices having pre-shared entanglement in order to operate. Therefore, the quantum part of the protocol is not truly local.

1.4 Notation

Below we will use calligraphic font to represent quantum algorithms (e.g. $\mathcal{Alg}$) and calligraphic font and/or the bracket notation for (mixed) quantum states (e.g. $s\mathcal{k}$ for a quantum secret key or $|\psi\rangle$). We will use standard math or sans serif font to represent classical algorithms (e.g. A or Alg) and classical variables (e.g. x for a classical one-letter variable or pk for a classical public key). A function $f : \mathbb{Z} \to \mathbb{R}^+$ is called negligible if $f(n) = o(n^{-c})$ for any constant c. We denote by $x \leftarrow S$ the random variable x generated by sampling uniformly at random from the set S. Similarly, we denote by $x \leftarrow D$ the random variable x generated by sampling according to the distribution D.

Common Reference String Model. As is the case with quantum lightning [45], a common reference string is necessary for most of the primitives we describe in this work. This is for the same reason we require a common reference string in collision resistant hash functions: for a fixed function there always exists an adversary that knows a collision. In the definitions below we assume that this common string is drawn uniformly at random. This is the ideal scenario and does not require any public parameters generator. In some cases, for example when the common reference string describes an obfuscated algorithm, a parameters generator may be necessary. In this case, this generator may hide a secret trapdoor which it destroys after publishing the common reference string.

2 EQUIVOCAL COLLISION RESISTANT HASH FUNCTIONS

In this section we define the new notion of equivocal collision-resistant hash functions and we give a construction relative to a classical oracle.

Definition 2.1 (Equivocal Hash-Functions). An equivocal hash function family is a triple of algorithms $(\mathcal{Gen}, \mathsf{Eval}, \mathcal{Equiv})$ with the following syntax:

> $\mathcal{Gen}(\mathsf{crs}) : (h, s\mathcal{k}, p)$ takes as input a common reference string crs and returns a hash value h, a quantum secret key $s\mathcal{k}$ and a description of a predicate p.
> $\mathsf{Eval}(\mathsf{crs}, x) : h$ takes as input a crs and a pre-image x and outputs a hash value h.
> $\mathcal{Equiv}(s\mathcal{k}, b) : x$ takes as input a quantum secret key $s\mathcal{k}$ and a bit b and returns a pre-image x.

Correctness requires that the following holds with overwhelming probability. If $(h, s\mathcal{k}, p) \leftarrow \mathcal{Gen}(\mathsf{crs})$ then for any bit b, it holds that $\mathsf{Eval}(\mathsf{crs}, x) = h$ and $p(x) = b$, where $x \leftarrow \mathcal{Equiv}(s\mathcal{k}, b)$.

The definition states that a quantum algorithm $(\mathcal{Gen}, \mathcal{Equiv})$ can sample an image h, a secret "inversion" quantum key $s\mathcal{k}$ as well as a predicate p as a polynomial size circuit, and later on, given any bit b, it can use this key to find a pre-image x of h such that $p(x) = b$. It is important to notice that if we also require collision resistance, then quantumness is necessary. If the secret key were classical, then by running $\mathcal{Equiv}$ twice with $b = 0$ and $b = 1$ we could find a collision. In the quantum case, running $\mathcal{Equiv}$ can make $s\mathcal{k}$ collapse and thus impossible to reuse.

Theorem 2.2. *There exists an equivocal collision resistant hash function relative to a classical oracle.*

In section 2.1 we define our scheme relative to a classical oracle. In sections 2.2 and 2.3 we prove the collision resistant and the equivocal property respectively.

In the process of coming up with an equivocal collision resistant hash function in the plain model, we note that it is enough to come up with a function that breaks the unequivocal property with an inverse polynomial probability. Given such a function H, we can easily boost to high success probability by running it independently n times. In particular, the function $H^n(x_1, \ldots, x_n) = (H(x_1), \ldots, H(x_n))$ is equivocal according to our definition. Let A be an adversary that breaks property (2). By running n times A we get values $h_1, \ldots, h_n$ and predicates $p_1, \ldots, p_n$. We define our predicate $p(x_1, \ldots, x_n)$ as the majority of $p_i(x_i)$. To equivocate to a bit b, we simply equivocate each individual hash to b. By invoking the Chernoff bound and choosing n large enough, we are guaranteed that we get a pre-image $x = x_1, \ldots, x_n$ such that $p(x) = b$ with overwhelming probability.

An interesting question that arises is whether (2) implies (3); namely, can we use a distinguisher against the collapsing property to build an inverter that equivocates? Although searching solutions looks like a harder task than just distinguishing two different states, the above implications are not excluded.

2.1 Construction Relative to a Classical Oracle

In this section we define our function family relative to a classical oracle. The oracle is a combination of two oracles $H, H^\perp$ where H is the evaluation oracle and $H^\perp$ is used to achieve equivocality. In our construction, the space of n-bit inputs is partitioned into $2^{n/2}$ affine spaces of dimension $n/2$. The oracle H assigns a distinct output to each space. Applying H to a uniform superposition and measuring yields a uniform superposition over one of the affine subspaces. To achieve the equivocal property, a second oracle $H^\perp$ is provided, which tests for membership in the spaces orthogonal to the affine spaces in H.

Before defining our construction we introduce some terminology. For the n-dimensional space $\mathbb{F}_2^n$, a d-ordered affine partition $P = (A_y)_{y \in \{0,1\}^{n-d}}$ is a list of 2^{n-d} pairwise disjoint affine subspaces of dimension d. For an affine subspace A, we denote $A^\perp$ the orthogonal complement of the linear subspace corresponding to A.

Definition 2.3 (Affine partition function). Let $P = (A_y)_{y \in \{0,1\}^{n/2}}$ be an $n/2$-ordered affine partition. An affine partition function $(H_P, H_P^\perp)$ is defined as:

- $H_P : \mathbb{F}_2^n \to \{0,1\}^{n/2}$ such that $H_P(x) = y$ if and only if $x \in A_y$,
- $H_P^\perp : \mathbb{F}_2^n \times \{0,1\}^{n/2} \to \{0,1\}$ such that $H_P^\perp(x, y) = 1$ if and only if $x \in A_y^\perp$.

In other words, our function is parameterized by an ordered partition of the whole n-dimensional input space into affine subpsaces, each containing $2^{n/2}$ points such that all points in the same

subspace A_y map to the same value y. Our claim is that there exists an affine partition that requires exponentially many queries to find a collision.

Theorem 2.4. *An affine ordered partition $P = (A_y)_{y\in\{0,1\}^{n/2}}$ exists such that H_P is an equivocal collision resistant hash function relative to the oracle $(H_P, H_P^{\perp})$.*

Notice that the above theorem claims worst-case hardness. We prove the two parts of this theorem in the following two subsections. In subsection 2.2 we prove our query complexity lower bound for collisions and in subsection 2.3 we prove equivocality.

2.2 Collision Resistance

Our collision resistance lower bound uses a modification of the inner-product adversary method [2, 4] and follows the lines of [10]. We devise a relation between hard-to-distinguish partitions and we prove that any algorithm that finds a collision must end up in states such that their average inner product (over the relation) is a constant away from 1. The relation is picked in such a way that the average inner product cannot decrease by more than an exponentially small amount in each query.

We will use the following generalization of Ambainis's [4] basic adversary method. It combines the inner product adversary method by Aaronson and Christiano [2] with Lemma 18 by Ben-David and Sattath [10].

Theorem 2.5 (Adversary method for search problems). *Let $S \subset \{0,1\}^N$ be a set of inputs of size N, $q : S \to T$ be a search problem and let $R \subset S \times S$ be a symmetric relation between inputs. For any $x \in S$, let $R_x = \{y \in S : (x,y) \in R\}$. If*

1. *(Hard-to-distinguish (x,y) pairs). For every x appearing in R and every $i : x_i = 0$, $\Pr_{y\leftarrow R_x}[y_i = 1] \le \varepsilon$,*
2. *(Distinguishing solutions s). For every x appearing in R and every $s : s \in q(x)$, $\Pr_{y\leftarrow R_x}[s \in q(y)] \le c$,*

then any quantum algorithm that solves q with an inverse polynomial in $\log N$ probability must make at least $\Omega\left(\frac{1-\sqrt{c}-d}{\sqrt{\varepsilon}}\right)$ queries to the input, where d is a negligible function in $\log N$.

Proof. Consider an input $x \in \{0,1\}^N$ and suppose that an algorithm A makes T queries; i.e., $A = U_T O_x U_{T-1} O_x \cdots U_1 O_x U_0$, where $U_1, \ldots, U_T$ are arbitrary unitary transformations independent of x and $O_x |i\rangle = (-1)^{x_i} |i\rangle$. Let $\left|\phi_t^x\right\rangle, \left|\psi_t^x\right\rangle$ be the states of the algorithm before after the t'th query to O_x. In the beginning $\left|\psi_1^x\right\rangle$ is the same for all x since A has not made any query to O_x. The final state of the algorithm is $\left|\phi_T^x\right\rangle$.

Consider the progress measure $p_t = \mathrm{E}_{(x,y)\leftarrow R}\left[\left|\left\langle\phi_t^x\middle|\phi_t^y\right\rangle\right|\right]$ and observe that $p_1 = 1$. We will prove that condition 1 implies that a single query cannot decrease the progress measure too much and condition 2 implies that anyone that finds a solution with good probability after T queries should end up having a progress p_T at least a constant less than 1.

We begin by proving that $p_{t-1} - p_t \le 4\sqrt{\varepsilon}$. The proof in a more general setting, where the oracles can be reflections across subspaces, first appeared in [2] but we include it here for completeness.

Write

$$\left|\phi_t^x\right\rangle = \sum_{i\in[N]} \alpha_{t,i}^x |i\rangle \left|\phi_{t,i}^x\right\rangle$$

where $\sum_{i\in[N]} \left|\alpha_{t,i}^x\right|^2 = 1$ and notice that

$$\left\langle\phi_t^x\middle|\phi_t^y\right\rangle = \sum_{i\in[N]} \overline{\alpha_{t,i}^x}\alpha_{t,i}^y \left\langle\phi_{t,i}^x\middle|\phi_{t,i}^y\right\rangle.$$

After we query O_x our new state becomes

$$\left|\psi_t^x\right\rangle = \sum_{i:x_i=0} \alpha_{t,i}^x |i\rangle \left|\phi_{t,i}^x\right\rangle - \sum_{i:x_i=1} \alpha_{t,i}^x |i\rangle \left|\phi_{t,i}^x\right\rangle$$

and thus

$$\left\langle\phi_t^x\middle|\phi_t^y\right\rangle - \left\langle\psi_t^x\middle|\psi_t^y\right\rangle = 2\sum_{i:x_i\neq y_i} \overline{\alpha_{t,i}^x}\alpha_{t,i}^y \left\langle\phi_{t,i}^x\middle|\phi_{t,i}^y\right\rangle.$$

Moreover, by the triangle inequality, we have that

$$\begin{aligned}\left|\left\langle\phi_t^x\middle|\phi_t^y\right\rangle\right| - \left|\left\langle\psi_t^x\middle|\psi_t^y\right\rangle\right| &\le \left|\left\langle\phi_t^x\middle|\phi_t^y\right\rangle - \left\langle\psi_t^x\middle|\psi_t^y\right\rangle\right| \\ &\le 2\sum_{i:x_i\neq y_i} \left|\alpha_{t,i}^x\right\|\alpha_{t,i}^y\right|\end{aligned}$$

Lemma 2.6 (Small progress [2]). *If for every x appearing in R and every $i : x_i = 0$, $\Pr_{y\leftarrow R_x}[y_i = 1] \le \varepsilon$, then $p_{t-1} - p_t \le 4\sqrt{\varepsilon}$.*

Proof. See full version of the paper. □

We continue by showing that any algorithm that finds a solution with constant probability should achieve p_T that is a constant away from 1. The following Lemma is a trivial generalization of Lemma 18 by Ben-David and Sattath [10].

Lemma 2.7. *Let R be a symmetric relation between inputs $x \in \{0,1\}^N$ and let $q : \{0,1\}^N \to \{0,1\}^{O(\log N)}$ be a search problem. Suppose that an algorithm computes q with probability at least $1-d$ after T queries. If $\max_{x,s\in q(x)} \Pr_{y\leftarrow R_x}[s \in q(y)] \le c$, then*

$$p_T \le \sqrt{c} + 2\sqrt{d}.$$

Proof. See full version of the paper. □

By combining the above lemmata 2.6 and 2.7, we conclude that any algorithm that finds a solution with probability at least $1-d$, has to make at least $\Omega\left(\frac{1-\sqrt{c}-2\sqrt{d}}{\sqrt{\varepsilon}}\right)$ queries to the input.

It remains to show that any algorithm that succeeds with probability at least $1/p(n)$, where $n = \log N$, for some polynomial p, can be turned into an algorithm that succeeds with probability close to 1. Indeed, by running our algorithm $p(n)q(n)$ times, where $q(n)$ is a polynomial, we get a winning probability of $1 - (1 - 1/p(n))^{p(n)q(n)} \approx 1 - e^{-q(n)}$ which is exponentially close to 1. Notice that the repetition reduces the lower bound by a polynomial factor of $p(n)q(n)$. This concludes the proof of theorem 2.5. □

Equipped with theorem 2.5, we can derive the first part of theorem 2.4; i.e., the existence of a partition that is collision resistant.

Theorem 2.8. *An affine ordered partition $P = (A_y)_{y\in\{0,1\}^{n/2}}$ exists such that H_P is a collision resistant hash function relative to the oracle $(H_P, H_P^{\perp})$.*

Proof. In our case, $S = \Sigma^{\mathbb{F}_2^n} \times \{0,1\}^{\mathbb{F}_2^n \times 2^{n/2}}$, where $\Sigma = \{0,1\}^{n/2}$ is the range of H_P, $T = \mathbb{F}_2^n \times \mathbb{F}_2^n$ and the search problem is defined as $\mathrm{col}(H_P, H_P^\perp) = \{(a,b) : H_P(a) = H_P(b) \wedge a \neq b\}$.

Define the relation R such that $((H_P, H_P^\perp), (H_Q, H_Q^\perp)) \in R$ if and only if for each $y \in \{0,1\}^{n/2}$, $\dim(A_y^P \cap A_y^Q) = n/2 - 1$, where $P = (A_y^P)_{y \in \{0,1\}^{n/2}}$. Fix an image y and a point $p \in A_y^P$. It holds that

$$\Pr_{Q \leftarrow R_P}[p \in A_y^Q] = \frac{\left|A_y^P \backslash A_y^Q\right|}{\left|\mathbb{F}_2^n \backslash A_y^P\right|} = \frac{2^{n/2-1}}{2^n - 2^{n/2}} \leq \frac{1}{2^{n/2}},$$

and, therefore, $\varepsilon = 1/2^{n/2}$. Moreover, any collision $p \neq q \in A_y^P$ forms a one-dimensional affine subspace $C = \{p, q\} \leq A_y^P$. We can see that the probability $\Pr_{q \leftarrow R_P}[C \leq A_y^Q]$ equals to the probability that $\{0, q+p\}$ belongs to the linear subspace $A_y^Q + p$. We have that

$$\begin{aligned}\Pr_{Q \leftarrow R_P}[C \leq A_y^Q] &= \Pr_{Q \leftarrow R_P}[\{0, p+q\} \leq A_y^Q + p] \\ &= \frac{\binom{n/2-1}{n/2-2}_2}{\binom{n/2}{n/2-1}_2} = \frac{2^{n/2-1}-1}{2^{n/2}-1} \leq \frac{1}{2},\end{aligned}$$

where $\binom{n}{k}_q = \prod_{i=0}^{k-1} \frac{1-q^{n-i}}{1-q^{k-i}}$ is the Gaussian binomial coefficient that counts the number of k-dimensional linear subspaces in $\mathbb{F}_q^n$. Therefore, we get that $c = 1/2$.

By invoking theorem 2.5 with $\varepsilon = 1/2^{n/2}$ and $c = 1/2$, we get that any algorithm that finds a collision with an inverse polynomial probability has to make $\Omega\left(2^{n/4}(.29 - d(n))\right)$ queries, where d is negligible.

□

2.3 Equivocality

In this subsection we prove the equivocal property. We define our algorithms $\mathcal{Gen}, \mathcal{Equiv}$ as follows. $\mathcal{Gen}$ first prepares the uniform superposition over all inputs $|\phi\rangle = 2^{-n/2} \sum_{x \in \mathbb{F}_2^n} |x\rangle$, then evaluates the oracle to get the state $|\psi\rangle = 2^{-n/2} \sum_x |x\rangle |H_P(x)\rangle$, measures the second register and gets $\left|A_y\right\rangle = 2^{-n/4} \sum_{x \in A_y} |x\rangle |y\rangle$ for a uniformly random y. $\left|A_y\right\rangle$ corresponds to the secret quantum key sk and y is the corresponding image. Now, given sk and any bit b, the goal of $\mathcal{Equiv}$ is to find a pre-image $x \in A_y$ such that x_1, the first bit of x, equals b.

Of course, for such an algorithm to work correctly it should be the case that A_y contains both x's that start with 0 and x's that start with 1. Since our complexity lower bound is for a worst case partition, it could be the case that all x's in the same affine subspace start with the same bit. To overcome this, we note that if $(H_P, H_P^\perp)$ is an affine partition function that is collision resistant, then for any full-rank linear transformation f, the function $(H_{P'}, H_{P'}^\perp)$, where $P' = (A'_y)_{y \in \{0,1\}^{n/2}}$ and $A'_y = \{f(x) : x \in A_y\}$ is also a collision resistant affine partition function. By applying a random linear transformation f, we retrieve a random affine subspace A. As long as one of the basis vectors in the corresponding linear subspace has 1 in its first coordinate, half of the elements in the linear subpspace will start with 0. The probability that a random subspace does not have a vector starting with 1 is $2^{-n/2}$ since it has to be the case that none of the $n/2$ basis vectors starts with 1.

Theorem 2.9 (Equivocality). *There is an affine ordered partition P such that H_P is an equivocal collision resistant hash function relative to the oracle $(H_P, H_P^\perp)$.*

Proof. Fix a P such that H_P is collision resistant and apply a random full-rank linear transformation on it. It suffices to show that given $\left|A_y\right\rangle$ and y as well as access to the oracle $H_P^\perp$, we can find an x such that $x \in A_y$ and x_1, the first bit of x, starts with the bit of our choice. Let $A_{y,b} = \{x \in A_y : x_1 = b\}$ and notice that $A_{y,0}$ is an affine subspace parallel to $A_{y,1}$. We first condition on $\left|A_{y,0}\right| = \left|A_{y,1}\right|$ since the probability of the event not happening is negligible. Our goal now is to run Grover's search algorithm in order to transform our state $\left|A_y\right\rangle$ into the state $\left|A_{y,b}\right\rangle$.

We would like to implement the following two oracles:

(1) $O_b = 2\sum_{x:x_1=b} |x\rangle\langle x| - I$ and
(2) $U_y = 2\left|A_y\right\rangle\left\langle A_y\right| - I = F\left(2\left|A_y^\perp\right\rangle\left\langle A_y^\perp\right| - I\right)F$, where F is the quantum Fourier Transform over $\mathbb{F}_2^n$ which is equivalent to the n-qubit Hadamard gate.

The oracle O_b can be implemented locally by running on superposition a classical function that accepts inputs that start with b and rejects otherwise. However, notice that in our case we do not have access to the quantum oracle $2\left|A_y^\perp\right\rangle\left\langle A_y^\perp\right| - I$ but instead to the classical oracle $H_P^\perp(\cdot, y) = 2\sum_{x \in A_y^\perp} |x\rangle\langle x| - I$ that accepts all vectors in the orthogonal subspace and not just their uniform superposition. We claim that this oracle is enough to implement Grover's algorithm. To see this, notice that Grover's algorithm runs on the 2-dimensional subspace spanned by $\left|A_{y,0}\right\rangle, \left|A_{y,1}\right\rangle$. It is therefore, enough to implement an oracle that accepts the state $|+\rangle = \left|A_y\right\rangle = \frac{1}{\sqrt{2}}(\left|A_{y,0}\right\rangle + \left|A_{y,1}\right\rangle)$ and rejects the state $|-\rangle = \frac{1}{\sqrt{2}}(\left|A_{y,0}\right\rangle - \left|A_{y,1}\right\rangle)$. Let $A_y = S_y + t$ for some translation t. Moreover let $A_{y,0} = S_{y,0} + a$ and $A_{y,1} = S_{y,0} + b$ such that $a_1 + b_1 = 1$ since both are translations of the same linear subpspace and their first bit differs. We have:

$$\begin{aligned}FH_P^\perp(\cdot, y)F|+\rangle &= FH_P^\perp(\cdot, y)\frac{1}{2^{n/4}}\sum_{x \in A_y^\perp}(-1)^{tx}|x\rangle \\ &= F\frac{1}{2^{n/4}}\sum_{x \in A_y^\perp}(-1)^{tx}|x\rangle \\ &= |+\rangle\end{aligned}$$

and

$$\begin{aligned}FH_P^\perp(\cdot, y)F|-\rangle &= FH_P^\perp(\cdot, y)\frac{1}{\sqrt{2}}(F\left|A_{y,0}\right\rangle - F\left|A_{y,1}\right\rangle) \\ &= FH_P^\perp(\cdot, y)\frac{1}{2^{(n+3)/4}}\left(\sum_{x \in A_{y,0}^\perp \backslash A_y^\perp}(-1)^{x(a+b)}|x\rangle\right) \\ &= F\frac{1}{2^{(n+3)/4}}\left(\sum_{x \in A_{y,0}^\perp \backslash A_y^\perp} -(-1)^{x(a+b)}|x\rangle\right) \\ &= -|-\rangle.\end{aligned}$$

Moreover, since we know the number of pre-images that start with the desired bit, we can calculate the exact number of iterations in order to find a correct solution with probability 1. □

3 ONE-SHOT CHAMELEON HASH FUNCTIONS

In our setting, we require a family of hash functions, indexed by a common reference string crs. This is to deal with trivial adversaries that always know a collision of a hash function. Second, we would like the image h to be sampled together with a quantum inversion key sk, which can be used later, to find randomness r for any input x. Formally, we have

Definition 3.1 (One-Shot Chameleon Hash Functions). A one-shot chameleon hash function is a tuple of algorithms $(\mathcal{Gen}, \mathsf{Eval}, \mathit{Inv})$ with the following syntax:

> $\mathcal{Gen}(\mathsf{crs}) : (h, sk)$ takes as input a common reference string crs and outputs a hash value h together with a quantum secret key sk,
> $\mathsf{Eval}(\mathsf{crs}, x, r) : h$ takes as input a common reference string crs, an input x and randomness r and outputs a hash h,
> $\mathit{Inv}(sk, x) : r$ takes as input a secret key sk and an x and outputs randomness r.

Correctness. The following holds with overwhelming probability over crs and the randomness of $\mathcal{Gen}$ and Inv. If $(h, sk) \leftarrow \mathcal{Gen}(\mathsf{crs})$ then for any input x, we have $\mathsf{Eval}(\mathsf{crs}, x, \mathit{Inv}(sk, x)) = h$.

Collision Resistance. For any polynomial quantum adversary $\mathcal{A}$, there is a negligible function ε such that

$$\Pr\left[\begin{array}{c}\mathsf{Eval}(\mathsf{crs}, x_0, r_0) = \\ \mathsf{Eval}(\mathsf{crs}, x_1, r_1)\end{array} \middle| \begin{array}{r}\mathsf{crs} \leftarrow \{0,1\}^n \\ \{(x_0, r_0), (x_1, r_1)\} \leftarrow \mathcal{A}(\mathsf{crs})\end{array}\right] \leq \varepsilon(n).$$

Theorem 3.2. *One-shot chameleon hash functions exist if and only if equivocal collision-resistant hash functions exist.*

Proof. The only if part is straightforward by setting the input length $|x| = 1$ to be a single bit and defining the predicate as $p(x, r) = x$. For the opposite direction, we first define our chameleon hash function $(\mathcal{Gen}, \mathsf{Eval}, \mathit{Inv})$ for messages of one bit. Let $(E.\mathcal{Gen}, E.\mathsf{Eval}, E.\mathcal{Equiv})$ be an equivocal CRHF. Define

> $\mathcal{Gen}(\mathsf{crs})$: Run $(h', sk, p) \leftarrow E.\mathcal{Gen}(\mathsf{crs})$, set $h = (h', p, 0)$ and return (h, sk).
> $\mathsf{Eval}(\mathsf{crs}, (p, b), r)$: Return $(E.\mathsf{Eval}(\mathsf{crs}, r), p, p(r) \oplus b)$
> $\mathit{Inv}(sk, (p, b))$: Run $r \leftarrow E.\mathcal{Equiv}(sk, b)$ and return r

Correctness is implied by the correctness of the equivocal CRHF.

For security, suppose that there exists an algorithm $\mathcal{A}$ and a non-negligible function e such that

$$\begin{aligned}\Pr[\mathcal{A}\text{ wins}] &= \Pr[\mathsf{Eval}(\mathsf{crs}, (p_0, b_0), r_0) = \mathsf{Eval}(\mathsf{crs}, (p_1, b_1), r_1)] \\ &= \Pr[E.\mathsf{Eval}(\mathsf{crs}, r_0) = E.\mathsf{Eval}(\mathsf{crs}, r_1) \wedge r_0 \neq r_1],\end{aligned}$$

where the probability is over crs and $\{(p_0, b_0, r_0), (p_1, b_1, r_1)\} \leftarrow \mathcal{A}(\mathsf{crs})$. An adversary who just runs $\{(p_0, b_0, r_0), (p_1, b_1, r_1)\} \leftarrow \mathcal{A}(\mathsf{crs})$ and returns (r_0, r_1) can also find a collision in the equivocal hash function with probability $e(n)$.

Using parallel repetition, we can get one-shot chameleon hash functions for longer messages. □

3.1 Signature Delegation

As illustrated in the introduction, one-shot signatures give rise to delegation of authentication where Alice can delegate Bob to sign a single message. The idea is to use the hash-then-sign paradigm [9] where in our case, the hash will be a one-shot chameleon hash.

Let $S' = (\mathsf{Gen}', \mathsf{Sign}', \mathsf{Ver}')$ be a standard signature scheme with existential unforgeability under chosen message attacks (EUF-CMA) and let $C = (\mathcal{Gen}, \mathsf{Eval}, \mathit{Inv})$ be a one-shot chameleon hash function. We define a signature scheme $S = (\mathsf{Gen}, \mathsf{Sign}, \mathsf{Ver})$ as:

> $\mathsf{Gen}(1^n)$: Run $(\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{Gen}'(1^n)$ and output $(\mathsf{pk}, \mathsf{sk})$.
> $\mathsf{Sign}(\mathsf{crs}, \mathsf{sk}, m)$: Pick a random r and then compute $h \leftarrow \mathsf{Eval}(\mathsf{crs}, m, r)$ and $\sigma \leftarrow \mathsf{Sign}'(\mathsf{sk}, h)$. Return (σ, r).
> $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, (\sigma, r))$: Compute $h \leftarrow \mathsf{Eval}(\mathsf{crs}, m, r)$ and return $\mathsf{Ver}'(\mathsf{pk}, h, \sigma)$.

It is easy to see that the correctness of S is implied by the correctness of S' and C. Moreover, S is EUF-CMA as long as S is also EUF-CMA and C is secure. Indeed if an adversary could create a new signature after querying a signing oracle, then one could use this adversary to break either the one-shot chameleon hashing or the original signature S'.

Delegation. Now suppose that Alice, who owns a classical computer, possesses a key pair $(\mathsf{pk}, \mathsf{sk})$ for S and she wishes to delegate Bob to sign a single message. To do this, Alice and Bob run the following 2-message protocol.

> Bob runs $(h, sk) \leftarrow \mathcal{Gen}(\mathsf{crs})$ and sends h to Alice.
> Alice runs $\sigma \leftarrow \mathsf{Sign}'(\mathsf{sk}, h)$ and sends σ to Bob.

Now Bob possesses a quantum key sk that he can use together with σ to sign any message m of his choice. To do this, Bob runs $r \leftarrow \mathit{Inv}(sk, m)$ and returns (σ, r) as the signature of m. By the correctness of S' and C we get that Bob's signature is accepted by Ver. Moreover, if a malicious Bob could come up with more than k signatures after running the above protocol k times, then he could also break S or C.

4 ONE-SHOT SIGNATURES AND BUDGET SIGNATURES

A one-shot signature scheme has the property that no one can create a public key together with two valid signatures.

Definition 4.1 (One-Shot Signatures). A one-shot signature is a tuple of algorithms $(\mathcal{Gen}, \mathcal{Sign}, \mathsf{Ver})$ with the following syntax:

> $\mathcal{Gen}(\mathsf{crs}) : (\mathsf{pk}, sk)$ takes a common reference string crs and outputs a classical public key pk and a quantum secret key sk.
> $\mathcal{Sign}(sk, m) : \sigma$ takes a secret key sk and a message m and outputs a signature σ.
> $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, \sigma) : b$ takes a common reference string crs, a public key pk, a message m and a signature σ and outputs a bit b.

Correctness. The following holds with overwhelming probability. If $(\mathsf{pk}, sk) \leftarrow \mathcal{Gen}(\mathsf{crs})$ then $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, \mathcal{Sign}(sk, m)) = 1$ for any message m.

Security. For any quantum polynomial time algorithm $\mathcal{A}$ there is a negligible function ε such that

$$\Pr\left[\begin{array}{l}\mathsf{Ver}(\mathsf{crs},\mathsf{pk},m_0,\sigma_0)\\ \mathsf{Ver}(\mathsf{crs},\mathsf{pk},m_1,\sigma_1)\end{array}\;\middle|\;\begin{array}{r}\mathsf{crs}\leftarrow\{0,1\}^n\\ (\mathsf{pk},\{(m_b,\sigma_b)\}_b)\leftarrow\mathcal{A}(\mathsf{crs})\end{array}\right]\leq\varepsilon(n).$$

One-shot chameleon hashing gives a direct way to build one-shot signatures:

Theorem 4.2. *One-shot signatures exist if one-shot chameleon hash functions exist.*

Proof. Let $(C.\mathcal{G}en, C.\mathsf{Eval}, C.\mathit{Inv})$ be a one-shot chameleon hash function. We define our signature scheme $(\mathcal{G}en, \mathcal{S}ign, \mathsf{Ver})$ as follows. $\mathcal{G}en(\mathsf{crs})$ runs $(h, s\mathcal{K}) \leftarrow C.\mathcal{G}en(\mathsf{crs})$ and returns $\mathsf{pk} = h$ as the public key and $s\mathcal{K}$ as the secret key. $\mathcal{S}ign(s\mathcal{K}, m)$ runs $r \leftarrow C.\mathit{Inv}(s\mathcal{K}, m)$ and returns $\sigma = r$ as the signature. $\mathsf{Ver}(\mathsf{crs},\mathsf{pk},m,\sigma)$ runs $h' = C.\mathsf{Eval}(\mathsf{crs}, m, \sigma)$ and accepts only if $h' = \mathsf{pk}$. Correctness and security are implied immediately from the correctness and the security of the underlying chameleon hash function. □

One-shot signatures are a specific case of a more flexible notion which we call budget signatures. In a budget signature scheme, a public key has an initial budget β and each signature has a cost $c \leq \beta$. One can use their secret key to sign messages until the budget is exhausted. Security requires than no adversary can come up with signatures whose total cost exceeds the budget.

Definition 4.3 (Budget Signatures). A budget signature scheme is a tuple of algorithms $(\mathcal{G}en, \mathcal{S}ign, \mathsf{Ver})$ with the following syntax:

> $\mathcal{G}en(\mathsf{crs},\beta) : (\mathsf{pk}, s\mathcal{K})$ takes a common reference string crs and a budget β and outputs a classical public key pk with budget pk.budget and a quantum secret key $s\mathcal{K}$ with budget $s\mathcal{K}$.budget.
> $\mathcal{S}ign(s\mathcal{K}, m, c) : (s\mathcal{K}', \sigma)$ takes a secret key $s\mathcal{K}$, a message m and a cost $c > 0$ and outputs an updated secret key $s\mathcal{K}'$ and a signature σ.
> $\mathsf{Ver}(\mathsf{crs},\mathsf{pk},m,\sigma,c) : b$ takes a common reference string crs, a public key pk, a message m, a signature σ and a cost c and outputs a bit b.

Correctness. The following hold with overwhelming probability. If $(\mathsf{pk}, s\mathcal{K}) \leftarrow \mathcal{G}en(\mathsf{crs}, \beta)$, then $\mathsf{pk.budget} = s\mathcal{K}.\mathsf{budget} = \beta$. Moreover, if $s\mathcal{K}.\mathsf{budget} \geq c$ and $(s\mathcal{K}', \sigma) \leftarrow \mathcal{S}ign(s\mathcal{K}, m, c)$ then $\mathsf{Ver}(\mathsf{crs},\mathsf{pk},m,\sigma,c) = 1$ and $s\mathcal{K}'.\mathsf{budget} = s\mathcal{K}.\mathsf{budget} - c$.

Security. For any quantum polynomial time algorithm $\mathcal{A}$ the following probability is negligible

$$\Pr\left[\begin{array}{c}\forall i, \mathsf{Ver}(\mathsf{crs},\mathsf{pk},m_i,\sigma_i,c_i)\\ \sum_i c_i > \mathsf{pk.budget}\end{array}\;\middle|\;\begin{array}{r}\mathsf{crs}\leftarrow\{0,1\}^n\\ (\mathsf{pk},\{(m_i,\sigma_i,c_i)\})\leftarrow\mathcal{A}(\mathsf{crs})\end{array}\right].$$

It is easy to see that by modifying Ver to additionally check whether $\mathsf{pk.budget} = c$, we immediately get one-shot signatures.

4.1 Budget Signatures

We get budget signatures from one-shot signatures by applying a variant of the Merkle signature scheme [35]. Our public key will be the pair (pk, β) where pk is an one-shot signature public key and β is the initial budget. To sign a message m with a signature of cost c, we first pick two pairs $(\mathsf{pk}_c, s\mathcal{K}_c) \leftarrow \mathcal{G}en(\mathsf{crs})$ and $(\mathsf{pk}_{\beta-c}, s\mathcal{K}_{\beta-c}) \leftarrow \mathcal{G}en(\mathsf{crs})$ and we generate $\sigma = \mathcal{S}ign(s\mathcal{K}, (\mathsf{pk}_c, c, \mathsf{pk}_{\beta-c}, \beta - c))$. This signature indicates that c budget has been given to pk_c and the rest to $\mathsf{pk}_{\beta-c}$. We then derive $\sigma = \mathcal{S}ign(s\mathcal{K}_c, m)$ and we return $(\mathsf{pk}_c, \mathsf{pk}_{\beta-c}, \sigma)$ as the signature of m. To verify the signature, we also need to verify that the budgets of the two keys sum to β. The details appear in the full version of the paper.

5 QUANTUM LIGHTNING AND QUANTUM MONEY

Definition 5.1 (Quantum Money with Classical Communication). A quantum money scheme with classical communication is a pair of interactive quantum algorithms $(\mathcal{S}, \mathcal{R})$ as well as a generation algorithm $\mathcal{G}en$ with the following syntax:

> $\mathcal{G}en(\mathsf{crs}) : (\mathsf{pk}, \mathit{coin})$ takes as input a common string crs and outputs a quantum coin coin and a public key pk.
> $\langle \mathcal{S}(\mathit{coin}), \mathcal{R}(\mathsf{crs},\mathsf{pk})\rangle_{\mathcal{R}} : (\mathit{coin}', b)$ is a classical protocol between $\mathcal{S}$ and $\mathcal{R}$ where at the end $\mathcal{R}$ outputs a quantum coin coin' and a bit b.
> To simplify notation we define two functions $\mathcal{C}oin, \mathcal{V}er$ as: $\mathcal{C}oin(\mathsf{crs},\mathsf{pk},\mathit{coin}) = \mathit{coin}'$ and $\mathcal{V}er(\mathsf{crs},\mathsf{pk},\mathit{coin}) = b$ if and only if $\langle \mathcal{S}(\mathit{coin}), \mathcal{R}(\mathsf{crs},\mathsf{pk})\rangle_{\mathcal{R}} = (\mathit{coin}', b)$.

Correctness. If $(\mathit{coin},\mathsf{pk}) \leftarrow \mathcal{G}en(\mathsf{crs})$ then $\mathcal{V}er(\mathsf{crs},\mathsf{pk},\mathit{coin}) = 1$ with overwhelming probability. Moreover, if $\mathcal{V}er(\mathsf{crs},\mathsf{pk},\mathit{coin}) = 1$ then $\mathcal{V}er(\mathsf{crs},\mathsf{pk},\mathcal{C}oin(\mathsf{crs},\mathsf{pk},\mathit{coin})) = 1$ with overwhelming probability.

Security. For an adversary $\mathcal{B}$ with input state s interacting with two honest receivers in an arbitrary way, let $\left\langle \mathcal{B}(s), \mathcal{R}^2(\mathsf{crs},\mathsf{pk})\right\rangle_{\mathcal{R}^2}$ be the two outputs bits of the two receivers. For any polynomial time quantum adversaries $\mathcal{A}, \mathcal{B}$, there is a negligible function ε such that

$$\Pr\left[\left\langle \mathcal{B}(s), \mathcal{R}^2(\mathsf{crs},\mathsf{pk})\right\rangle_{\mathcal{R}^2} = (1,1)\;\middle|\;\begin{array}{r}\mathsf{crs}\leftarrow\{0,1\}^n\\ (\mathsf{pk},s)\leftarrow\mathcal{A}(\mathsf{crs})\end{array}\right]\leq\varepsilon(n).$$

Notice that the above definition generalizes the notion of quantum money. Indeed, if we allow quantum communication in the above protocol, then we can essentially get a single message protocol where the sender sends the coin to the receiver. Moreover, notice that interaction is necessary for sending a coin through a classical channel. Otherwise, one could simply copy the classical information and send it to multiple recipients.

5.1 Construction

We use our signature delegation mechanism to build our quantum money scheme. Intuitively, our coin will consist of a list of pairs $(\mathsf{pk}_1, \sigma_1), \ldots, (\mathsf{pk}_{n-1}, \sigma_{n-1})$ together with the pair $(\mathsf{pk}_n, s\mathcal{K}_n)$. To send our coin to someone, we first receive from them a new public key pk_{n+1}. We then use our quantum secret key to generate a signature $\sigma_{n+1} \leftarrow \mathcal{S}ign(s\mathcal{K}_{n+1}, \mathsf{pk}_{n+1})$ and we send the list $(\mathsf{pk}_1, \sigma_1), \ldots, (\mathsf{pk}_n, \sigma_n)$. To verify, the receiver checks that $\mathsf{pk}_1 = \mathsf{pk}$ and that all signatures in the list are valid.

Let $(\mathcal{G}en, \mathcal{S}ign, \mathsf{Ver})$ be a one-shot signature. We define our quantum money scheme $(\mathcal{G}en', \mathcal{S}, \mathcal{R})$ as follows.

> $\mathcal{G}en'(\mathsf{crs})$: run $(\mathsf{pk}, s\mathcal{K}) \leftarrow \mathcal{G}en(\mathsf{crs})$. Set $\mathit{coin} = (\mathsf{pk}, s\mathcal{K})$ and return $(\mathsf{pk}, \mathit{coin})$.

$\mathcal{S}(coin)$: Parse $coin = [(\mathsf{pk}_i, \sigma_i)]_{i\in[k-1]}, (\mathsf{pk}_k, sk_k)$. Receive pk from $\mathcal{R}$. Generate $\sigma_k \leftarrow \mathcal{Sign}(sk_k, \mathsf{pk})$ and, finally, send $[(\mathsf{pk}_i, \sigma_i)]_{i\in[k]}$ to $\mathcal{R}$.
$\mathcal{R}(\mathsf{crs}, \mathsf{pk}')$: Generate $(\mathsf{pk}, sk) \leftarrow \mathcal{Gen}(\mathsf{crs})$ and send pk to $\mathcal{S}$. Receive $[(\mathsf{pk}_i, \sigma_i)]_{i\in[k]}$ from $\mathcal{S}$. Assert that $\mathsf{pk}_1 = \mathsf{pk}'$ and $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}_i, \mathsf{pk}_{i+1}, \sigma_i) = 1$ for all $i \in [k-1]$, where $\mathsf{pk}_k = \mathsf{pk}$ and set $b = 1$. Else $b = 0$. Set $coin = [(\mathsf{pk}_i, \sigma_i)]_{i\in[k]}, (\mathsf{pk}, sk)$. Return $(coin, b)$.

Clearly the above scheme is correct. For security, suppose there is an adversary that can interact with two honest receivers and can convince them with respect to the same public key pk. This implies that the receivers sent $\mathsf{pk}_{k+1}, \mathsf{pk}'_{k+1}$ such that $\mathsf{pk}_{k+1} \neq \mathsf{pk}'_{k+1}$ with overwhelming probability and the adversary replied with classical messages $[(\mathsf{pk}_i, \sigma_i)]_{i\in[k]}$, $[(\mathsf{pk}'_i, \sigma'_i)]_{i\in[k']}$, such that $\mathsf{pk}_1 = \mathsf{pk}'_1 = \mathsf{pk}$ and all signatures are valid. Therefore, there exists an $i \in [k-1]$ such that $\mathsf{pk}_i = \mathsf{pk}'_i$ but $\mathsf{pk}_{i+1} \neq \mathsf{pk}'_{i+1}$. Thus, the adversary has been able to create two signatures for the same public key, breaking the security of one-shot signatures. In the blockchain terminology, the adversary has been able to come up with a fork in the chain of signatures.

Full scheme and value of a coin. The above definition and construction are a "mini-scheme" version of a quantum money scheme, and the most essential tool in building quantum money. As shown in [2], a trusted mint can then use a classical post-quantum signature scheme to sign the public key of the coin. Using our budget signatures we can get additional flexibility from our quantum money scheme. Now the mint instead of signing pk, it can sign the pair (pk, V) to mint a coin of value V. We can then view such a coin as a budget signature with total budget V. One can spend any fraction of V by simply signing the receivers' public keys with different costs.

5.2 Decentralized Cryptocurrency

As already argued by Zhandry [45], there is a way of getting decentralized blockchain-less cryptocurrencies by combining quantum lightning with proofs of work. One-shot signatures are a special case of quantum lightning. Indeed, the secret key sk of a one-shot signature can be used as a bolt. To verify the bolt, we just need to pick two messages $m_0 \neq m_1$ and then sign the first but without measuring in the end. Then run the verification algorithm to verify that the signature is valid. If this is the case, measuring the output bit will not disturb the state and thus we can rewind, sign the second message, again without measuring and subsequently, verify the signature. Finally, we rewind again to retrieve the initial sk.

The idea behind building a decentralized cryptocurrency out of quantum lightning is to consider a bolt $(\mathsf{pk}, bolt)$ valid only if $H(\mathsf{pk})$ (or just pk) is small; e.g. starting with at least k zeros. Thus, a user will have to spend a considerable amount of computational power in order to come up with such a bolt. However, using quantum lightning we can only transfer a coin quantumly. By replacing quantum lightning with one-shot signatures we can achieve a cryptocurrency that can also be transferred classically. Indeed, the only difference between a full blown quantum money scheme from a decentralized cryptocurrency scheme is the way we verify the first public key pk_1 in the list of public-key, signature pairs: in a quantum money scheme we want a signature of pk_1 under the mint's public key, whereas in a decentralized cryptocurrency we want that pk_1 is considerably small. Arguably, as explained by Zhandry [45], such a decentralized cryptocurrency would suffer from huge inflation as technology improves.

6 ORDERED SIGNATURES

In an ordered signature scheme, every message is signed with respect to a tag t. Unlikely one-shot signatures, we will allow the signer to sign any number of messages with associated tags. However, security sill insist that the tags signed must be in *increasing* order. That is, once the signer signs a message relative to tag t, it will become impossible to sign a message relative to a tag $t' < t$.

We will model security as follows. Consider a signing adversary $\mathcal{S}$ and a receiver adversary $\mathcal{R}$. Here, $\mathcal{S}$ will send valid message/tag/signature (m, t, σ) triples to $\mathcal{R}$. At the end of the interaction, $\mathcal{R}$ outputs a bit b.

We will consider a special class of adversaries, called *ordered signers*, which only outputs signed messages where the tags are in increasing order. To formalize the fact that an adversary can sign a message and keep it for later, we have $\mathcal{S}$ additionally interacts with a database D, where:

- D stores triples (m, t, σ). D is initially empty.
- $\mathcal{S}$ has arbitrary read access to D.
- $\mathcal{S}$ can write a triple to D only if (1) the signature is valid, and (2) the tag t is larger than any tag already present in D.
- $\mathcal{S}$ can only send messages to $\mathcal{R}$ if they are in D.

Definition 6.1 (Ordered Signatures). An ordered signature scheme is a tuple of algorithms $(\mathcal{Gen}, \mathcal{Sign}, \mathsf{Ver})$ with the following syntax:

$\mathcal{Gen}(\mathsf{crs}) : (\mathsf{pk}, sk)$ takes a common reference string crs and outputs a classical public key pk and a quantum secret key sk.
$\mathcal{Sign}(sk, m, t) : (sk', \sigma)$ takes a secret key sk, a message m, and tag t, and outputs an updated secret key sk' and a signature σ.
$\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, t, \sigma) : b$ takes a common reference string crs, a public key pk, a message m, a tag t, and a signature σ and outputs a bit b.

Correctness. For any sequence $(m_1, t_1), \ldots, (m_n, t_n)$ such that $t_1 < \cdots < t_n$, the following hold with overwhelming probability. Let $(\mathsf{pk}, sk_0) \leftarrow \mathcal{Gen}(\mathsf{crs})$. Then for $i = 1, \ldots, n$, let $(sk_i, \sigma_i) \leftarrow \mathcal{Sign}(sk_{i-1}, m_i, t_i)$. Then we have that $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_i, t_i, \sigma) = 1$ for all i.

Security. For any quantum polynomial time signing adversary $\mathcal{S}$ and any quantum polynomial time receiver adversary $\mathcal{R}$, there is an ordered signing adversary $\mathcal{S}'$ such that $\mathcal{R}$ has negligible advantage in distinguishing $\mathcal{S}$ from $\mathcal{S}'$.

We construct our ordered signatures using a chain of keys and signatures, similar to signature delegation. A signature includes the entire chain, and we leave open the problem of creating more succinct signatures, for example using composable SNARKs. The high-level idea is to generate a length-increasing chain of signatures, where each signature signs the tuple (pk', m, t) where t is the tag and pk' is the new public key. To verify the signature one has to

additionally check that the tags in the chain appear in increasing order.

6.1 Key Evolving Signatures and Proof of Stake Blockchains

We first recall the definition of key-evolving signatures. There are a few variants; for simplicity we will focus on the simplest variant which is called forward-secure signatures, (for a summary of related definitions, see [34]). A forward-secure signatures is comprised of four algorithms, (Gen, Upd, Sign, Ver)

The algorithm Gen produces sk_0, while the update function $\mathsf{Upd}(\mathsf{sk}_i) : \mathsf{sk}_{i+1}$, for any $i \geq 0$ transitions the key to the next period. The unforgeability property of a forward-secure signature postulates that a complete key-exposure at period $i \geq 0$ maintains the unforgeability of messages in any period $i' < i$.

Constructing a forward-secure signature scheme given an ordered signature $(\mathit{Gen}', \mathit{Sign}', \mathsf{Ver}')$ is described below. Note we assume, without loss of generality, that 0 belongs to the message space of the signing algorithm Sign'.

> $\mathit{Gen}(\mathsf{crs})$: given the common reference string crs, it runs $\mathit{Gen}'(\mathsf{crs})$ to obtain the classical public key pk' and the quantum secret key sk'. Subsequently it sets $\mathsf{pk} = \mathsf{pk}'$ and $sk = (sk', 0, 0)$.
> $\mathit{Sign}(sk, m)$: Parse $sk = (sk', i, j)$, run $\mathit{Sign}'(sk', m, (i, j+1))$ to obtain the updated secret key sk'' and the signature σ'. Subsequently, update the forward-secure secret-key to $sk = (sk'', i, j+1)$ and return the signature $\sigma = (\sigma', i, j+1)$.
> $\mathsf{Upd}(sk)$: Parses $sk = (sk', i, j)$, run $\mathit{Sign}'(sk', 0, (i+1, 0))$ to obtain the updated secret key sk'' and the signature σ'. Subsequently, update the forward-secure secret-key to $sk = (sk'', i+1, 0)$.
> $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, i, \sigma)$: Parse $\sigma = (\sigma', i', j')$ and then return $\mathsf{Ver}'(\mathsf{crs}, \mathsf{pk}, m, i', j', \sigma') = 1$ and $i = i'$, where Ver' validates the lexicographic ordering over the pairs (i, j).

Theorem 6.2. *The forward-secure signature* $(\mathit{Gen}, \mathsf{Upd}, \mathit{Sign}, \mathsf{Ver})$ *defined above is unforgeable if the underlying* $(\mathsf{Gen}', \mathit{Sign}', \mathsf{Ver}')$ *is a secure ordered signature.*

Proof. The proof follows easily from the lexicographic ordering over the pairs (i, j) and the security of the underlying signature. In particular consider any compromise at epoch i and the issue of an additional message associated with tag (i', j) for $i' < i$ in the underlying ordered signature. Given that tag $(i, 0) > (i', j)$ is already signed (as the security experiment has advanced to epoch i) we obtain directly an attack against the underlying ordered signature. □

Based on the above, the application of ordered signatures in the Proof-of-Stake (PoS) blockchain setting follows relatively simply. In a PoS protocol, participants that maintain the blockchain issue protocol messages (e.g., blocks of transactions) that are signed by a signature key associated to the account of the issuer. The signature is connected to the particular round of the protocol execution and this is an essential part of verification. Security in PoS protocols is argued, among other conditions, under an assumption on the total stake controlled by the adversary [6, 14, 29]. In a long range attack, see e.g., [13, 27], the adversary corrupts an old address that used to possess a high amount of stake, but at the current point of the execution its stake is depleted or is much less than the bound imposed on the adversary. Subsequently, the adversary, who now controls a high amount of stake at some past point of the execution, takes advantage of way the PoS protocol operates to simulate a "fake" but otherwise legitimate protocol execution that leads to failure of consistency in the view of a participant that joins the protocol execution at that moment. To mitigate this attack PoS systems either introduce setup assumptions [18, 29], or require secure erasures [6, 14] and employ some type of key-evolving signature. Solving this problem in the erasure model, where it is impossible to erase past protocol states and these become available when a participant is corrupted by the adversary, is deemed impossible (cf. [18] for a formalisation of this impossibility statement). It is easy to see that using an ordered signature key as part of the public-key of each participant in the PoS system and then using the current round as the tag in the underlying ordered signature would easily solve the problem and circumvent the impossibility. A corruption of an account at a round r, would still make it infeasible to reissue a signature with a tag $t' < t$ and hence produce an alternative protocol execution is infeasible under the security of the underlying ordered signature.

6.2 Provably Secret Signing Keys

Definition 6.3 (Single Signer Security). A signature scheme is single signer secure if for any quantum polynomial time adversaries $\mathcal{A}, \mathcal{A}_0, \mathcal{A}_1$, and for any efficiently sampleable distributions D_0, D_1 with super-logarithmic min-entropy over the message space, there is a negligible function ε such that

$$\Pr\left[\begin{array}{l|r} \mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_0, \sigma_0) = 1 & \mathsf{crs} \leftarrow \{0,1\}^n \\ \mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_1, \sigma_1) = 1 & (\mathsf{pk}, sk_0, sk_1) \leftarrow \mathcal{A}(\mathsf{crs}) \\ & m_0 \leftarrow D_0 \\ & m_1 \leftarrow D_1 \\ & \sigma_0 \leftarrow \mathcal{A}_0(sk_0, m_0) \\ & \sigma_1 \leftarrow \mathcal{A}_1(sk_1, m_1) \end{array}\right] \leq \varepsilon(n),$$

where sk_0, sk_1 can potentially be entangled.

The above definition aims to capture a particular type of attacks that we call splitting attacks. In such an attack, one may try to split a secret key into two secret keys that potentially sign different sets of messages; for example sk_0 may sign messages that begin with 0 and sk_1 may sign messages that begin with 1.

Theorem 6.4 (Ordered Signatures to Single Signers). *Single signer signatures exist if ordered signatures exist.*

6.3 From Ordered Signatures to Delayed Signatures

Definition 6.5 (δ-Delay Signatures). A delay signature scheme is a tuple of algorithms $(\mathit{Gen}, \mathit{Sign}, \mathsf{Ver})$ with the following syntax:

> $\mathit{Gen}(\mathsf{crs}) : (\mathsf{pk}, sk)$ takes a common reference string crs and outputs a classical public key pk and a quantum secret key sk.
> $\mathit{Sign}(sk, m, \mathsf{rd}, \mathsf{fd}) : (sk', \sigma)$ takes a secret key sk, a message m, a reverse delay rd, and a forward delay fd and outputs an updated secret key sk' and a signature σ.

$\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m, \mathsf{rd}, \mathsf{fd}, \sigma) : b$ takes a common reference string crs, a public key pk, a message m, a reverse delay rd, and a forward delay fd and a signature σ and outputs a bit b.

Correctness. For any sequence $(m_1, \mathsf{rd}_1, \mathsf{fd}_1), \ldots, (m_n, \mathsf{rd}_n, \mathsf{fd}_n)$, the following holds with overwhelming probability. Let $(\mathsf{pk}, sk_0) \leftarrow \mathcal{G}en(\mathsf{crs})$. Then for $i \in [n]$, let $(sk_i, \sigma_i) \leftarrow \mathcal{S}ign(sk_{i-1}, m_i, \mathsf{rd}_i, \mathsf{fd}_i)$. Then we have that $\mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_i, \mathsf{rd}_i, \mathsf{fd}_i, \sigma) = 1$ for all i.

δ-Delay. For any wall-clock time delta T, any pair of delays $(\mathsf{rd}_1, \mathsf{fd}_1), (\mathsf{rd}_2, \mathsf{fd}_2)$, any efficiently sampleable distributions D_0, D_1 with super-logarithmic min-entropy over the message space, and any quantum polynomial time adversaries $\mathcal{A} = (\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3)$, when the wall-clock time delta between the start of $\mathcal{A}_2$ and the completion of $\mathcal{A}_3$ is at most $(1-\delta)T$, the following probability is negligible,

$$\Pr\left[\begin{array}{l|r} \mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_0, \mathsf{rd}_0, \mathsf{fd}_0, \sigma_0) & \mathsf{crs} \leftarrow \{0,1\}^n \\ \mathsf{Ver}(\mathsf{crs}, \mathsf{pk}, m_1, \mathsf{rd}_1, \mathsf{fd}_1, \sigma_1) & (\mathsf{pk}, sk_0) \leftarrow \mathcal{A}_1(\mathsf{crs}) \\ & m_0 \leftarrow D_0 \\ & m_1 \leftarrow D_1 \\ & \sigma_0 \leftarrow \mathcal{A}_2(sk_0, m_0, \mathsf{rd}_0, \mathsf{fd}_0) \\ & \sigma_1 \leftarrow \mathcal{A}_3(sk_1, m_1, \mathsf{rd}_1, \mathsf{fd}_1) \end{array}\right].$$

We build our delay signatures on ordered signatures and the incremental proof of sequential work of Dottling et al.[20]. Here we impose that the signer runs a proof of sequential work in the background that has to be included as part of the signature. To verify the signature one has also to verify the corresponding proof of work.

7 PROOFS OF QUANTUMNESS AND MIN-ENTROPY

In this section we show that one-shot signatures can be used to create public-coin interactive proofs of quantumness and min-entropy.

7.1 Proofs of Quantumness

For interactive (possibly quantum) algorithms P, V, let $\langle P, V\rangle$ be the output of V after interacting with P.

Definition 7.1. A public-coin interactive proof of quantumness is a pair of interactive algorithms $(\mathcal{P}, \mathsf{V})$, where $\mathcal{P}$ is quantum and V is classical. $\mathcal{P}$ and V run a classical multi-round protocol in which, at each round, Ver picks a random message $m \leftarrow \{0,1\}^n$ and sends it to $\mathcal{P}$.

Correctness. $\langle \mathcal{P}(\mathsf{crs}), \mathsf{V}(\mathsf{crs})\rangle = 1$ with overwhelming probability over crs and the randomness of $\mathcal{P}$.

Security. For any classical polynomial time adversary P^*, there is a negligible function ε such that

$$\Pr\left[\langle P^*(\mathsf{crs}), \mathsf{V}(\mathsf{crs})\rangle = 1 \middle| \mathsf{crs} \leftarrow \{0,1\}^n\right] \leq \varepsilon(n).$$

Theorem 7.2. *A 3-message public-coin interactive proof of quantumness exists if one-shot signatures exist.*

In the construction, the prover first commits to a public key. Upon receiving a random message from the verifier, he signs it using the one-shot key and sends back the signature. To turn this protocol into non-interactive it is sufficient to invoke the classical Fiat-Shamir transformation [22].

Theorem 7.3. *A publicly verifiable non-interactive proof of quantumness exists in the random oracle model if one-shot signatures exist.*

7.2 Certifiable Min-Entropy

Similarly to a proof of quantumness, a proof of min-entropy is a protocol between a prover and a verifier at the end of which, the verifier outputs a string r of n bits together with a bit b. Correctness requires that at the end of the protocol the entropy of r is n. Security states that if the verifier accepts ($b = 1$) then r has to have super-logarithmic min-entropy. For a random variable r of n bits, the min-entropy of r is defined as $H_{\min}(r) = -\log \max_{x \in \{0,1\}^n} \Pr[x = r]$.

Definition 7.4. A public-coin interactive proof of min-entropy is a pair of interactive algorithms $(\mathcal{P}, \mathsf{V})$, where $\mathcal{P}$ is quantum and V is classical. $\mathcal{P}$ and V run a classical multi-round protocol in which, at each round, Ver picks a random message $m \leftarrow \{0,1\}^n$ and sends it to $\mathcal{P}$.

Correctness. $\langle \mathcal{P}(\mathsf{crs}), \mathsf{V}(\mathsf{crs})\rangle = (1, r)$ and $H_{\min}(r) = n$ with overwhelming probability over crs and the randomness of $\mathcal{P}$.

Security. For any quantum polynomial time adversary $\mathcal{P}^*$ and for any polynomial p, there is a negligible function ε such that

$$\Pr\left[\begin{array}{c} \langle \mathcal{P}^*(\mathsf{crs}), \mathsf{V}(\mathsf{crs})\rangle = (1, r) \\ H_{\min}(r) \leq \log p(n) \end{array} \middle| \mathsf{crs} \leftarrow \{0,1\}^n\right] \leq \varepsilon(n).$$

The protocol is almost identical to the protocol for proof of quantumness. The only difference is that the verifier also outputs the public key of the prover as the source of randomness.

Theorem 7.5. *A 3-message public-coin interactive proof of min-entropy exists if one-shot signatures exist.*

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