

Zero-Knowledge Shuffle Improvement in Ethereum Single Secret Leader Election

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Abstract—This is the abstract Zero-Knowledge Proof (ZKP) [1].

Index Terms—Ethereum, Proof of Shuffle, Distributed Systems, Inner Product Arguments, Zero-Knowledge Proof

1 INTRODUCTION

Ethereum is a decentralized blockchain platform that enables developers to build and deploy smart contracts and decentralized applications. It is the second-largest blockchain platform by market capitalization and has a large and active developer community.

2 BACKGROUND

In this section, we provide the necessary background information on Ethereum and a specific attack it is vulnerable to, the Curdleproofs protocol [2], and the Whisk protocol [3]

The notation used throughout this paper can be seen in Table 1.

Since this work is based on the existing Curdleproofs protocol [2], it inherits the same security assumptions. Our work therefore runs as a public coin protocol in any cryptographic group where Decisional Diffie-Hellman (DDH) is hard [4]. DDH is defined as follows.

Definition 1 (DDH). *Given a finite, multiplicative cyclic group \mathbb{G} of prime order p , the decisional Diffie-Hellman problem is defined as follows: Given $(g^a, g^b, g^c) \in \mathbb{G}$, where g is a generator of \mathbb{G} and $a, b, c \in \mathbb{Z}_p$, decide whether $c = ab$.*

2.1 Whisk

Ethereum uses a proof-of-stake consensus mechanism, which allows users to validate transactions and create new blocks by staking their Ether (ETH) tokens. The Proof-of-stake protocol works in epochs of 32 slots, where each slot is 12 seconds long. In each slot a proposer is chosen to propose a block thereby allowing the network to reach consensus on the state of the blockchain.

The proposer DoS attack is a type of attack that targets the block proposers making them unable to propose blocks.

An adversary can use the proposer DoS attack to prevent a proposer from receiving rewards, gotten from proposing a block, and increase their own rewards [5]. As a response to the proposer DoS attack, Ethereum has proposed a new protocol called Whisk [3] as an attempt to mitigate the attack. An attack on the Ethereum network that was discovered by Heimbach et al. [6] is the deanonymization attack on validators. In our preliminary work [7], we have shown that the attack is still possible to perform on the Ethereum network, and using the attack, a proposer Denial-of-Service (DoS) can be performed.

Whisk is a zero-knowledge Single Secret Leader Election (SSLE) system that uses a zero-knowledge argument called Curdleproofs [2] to verify the correctness of a shuffle without revealing the input or output [8]. Whisk works by selecting a list of 16,384 validator trackers and shuffles them over 8,192 slots (~ 1 day). Then 8,192 proposers are selected from the shuffled list to propose blocks for the next 8,192 slots while a new list is being shuffled. This way a new list of proposers is created every day. After each shuffle, Whisk uses a zero-knowledge proof to prove that the shuffle is correct. This is so that the proposer can prove that they are the correct proposer for the slot without revealing their identity, thereby mitigating the proposer DoS attack because of the identity of the upcoming proposers being hidden now.

Curdleproofs is a zero-knowledge proof system that allows a prover to prove knowledge of a shuffle without revealing how it shuffled the elements. It does so by using three different zero-knowledge proofs, with one of them relying on two more zero-knowledge proofs.

The first proof is the Same Permutation (SamePerm) proof. The prover first constructs a commitment to the permutation, $\sigma()$, by saying $M = \sigma(1, 2, \dots, \ell) \times \mathbf{g}$. Then, using the Fiat-Shamir transformation, a challenge, \mathbf{a} , from public inputs is constructed, and a new commitment is made from that, $A = \sigma(\mathbf{a}) \times \mathbf{g}$. The SamePerm proof now consists of convincing the verifier that the same permutation was used for constructing commitment A and M . To do this, the two commitments are used to construct a polynomial equation. Then Neff's trick [9] is used, which observes that two polynomials are equal iff. their roots are the same up to permutation.

To prove that, the protocol makes use of a grand product argument. To prove that argument, Curdleproofs compiles it down to an Inner Product Argument (IPA) by expressing each multiplication of the grand product as its own equa-

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Symbol	Description
\mathbb{G}	Cyclic, additive, group of prime order p
\mathbb{Z}_p	Ring of integers modulo p
$\mathbb{G}^n, \mathbb{Z}_p^n$	Vector spaces of dimension n over \mathbb{G} and \mathbb{Z}_p
\mathbb{Z}_p^*	Multiplicative group $\mathbb{Z}_p \setminus \{0\}$
$H \in \mathbb{G}$	Generator of \mathbb{G}
$\gamma \in \mathbb{Z}_p^{[\log n]}$	Uniformly distributed challenges
$\mathbf{a} \in \mathbb{F}^n$	Vector $\mathbf{a} = (a_1, \dots, a_n) \in \mathbb{F}^n$
$\mathbf{A} \in \mathbb{F}^{n \times m}$	Matrix with n rows and m columns
$\mathbf{b} = c \cdot \mathbf{a} \in \mathbb{Z}_p^n$	The vector where $b_i = c a_i$, with scalar $c \in \mathbb{Z}_p$ and $\mathbf{a} \in \mathbb{Z}_p^n$
$\mathbf{a} \times \mathbf{b} = \sum_{i=1}^n a_i \cdot b_i$	Inner product of $\mathbf{a}, \mathbf{b} \in \mathbb{F}^n$
$\mathbf{G} = (g_1, \dots, g_n) \in \mathbb{G}^n, \mathbf{G}' = (g'_1, \dots, g'_n) \in \mathbb{G}^n$	Vectors of generators (for Pedersen commitments)
$A = \mathbf{a} \times \mathbf{G} = \sum_{i=1}^n a_i \cdot G_i$	Binding (but not hiding) commitment to $\mathbf{a} \in \mathbb{Z}_p^n$
$\mathbf{r}_A \in \mathbb{Z}^n$	Blinding factors, e.g. $A = \mathbf{a} \times \mathbf{G} + \mathbf{r}_A \times \mathbf{G}$ is a Pedersen commitment to \mathbf{a}
$\mathbf{a} \parallel \mathbf{b} \in \mathbb{Z}_p^{n+m}$	Concatenation: if $\mathbf{a} \in \mathbb{Z}_p^n, \mathbf{b} \in \mathbb{Z}_p^m$, then $\mathbf{a} \parallel \mathbf{b} \in \mathbb{Z}_p^{n+m}$
$\mathbf{a}_{[1:k]} = (a_1, \dots, a_k) \in \mathbb{F}^k, \mathbf{a}_{[k:n]} = (a_{k+1}, \dots, a_n) \in \mathbb{F}^{n-k}$	Slices of vectors (Python notation)
$\{\phi; w \mid \text{properties satisfying } \phi, w\}$	Relation using the specified public input ϕ and private witness w

TABLE 1: Notation used throughout the paper.

tion.

Hence, the SamePerm proof is done if the prover can prove the IPA.

The second proof is a Same Multiscalar (SameMSM) argument. The prover should by now have proven the existence of the permutation. Now, the goal of the SameMSM argument is to prove that the output ciphertext set was constructed with the same permutation, here called multiscalar, committed to in commitment A . As the multiscalar is a vector this argument is an IPA by nature, contrary to the SamePerm argument.

The third proof is a Same Scalar argument. To mask the ciphertexts, each prover, besides permuting the set, multiplies all ciphertexts by a scalar, k . This is for randomization purposes, making it harder for adversaries to track the ciphertexts [3]. Also, all validators are still able to open their commitments if they are chosen as block proposers, even after several randomizations. So, the goal of the Same Scalar argument is to prove the existence of the scalar, k , such that the commitment of the permuted set is equal to the commitment of the pre-permuted set multiplied by k .

2.2 Zero-knowledge proofs

Curdleproofs is a zero-knowledge proof system, which means that it allows a prover to convince a verifier that they know a secret without revealing the secret itself. Within the context of Ethereum it could be the ability to convince someone that a transaction is valid without revealing information about the transaction such as the value of it. In Whisk, it uses Curdleproofs to prove the validity of a shuffle.

Definition 2 (Zero-Knowledge Argument of Knowledge). *An argument (Setup, P, V) is a zero-knowledge argument of knowledge of a relation \mathbb{R} if it satisfies completeness, knowledge-soundness and is honest-verifier zero-knowledge.*

Definitions for knowledge-soundness, completeness, and Honest-Verifier Zero-Knowledge (HVZK) can be found in section A.

2.3 Problem definition

In Chapter 6 of Curdleproofs [2], they explain the efficiency of the protocol, including also the size of the

proof. They specifically mention that the proof has size $18 + 10 \log(\ell + 4)\mathbb{G}, 7\mathbb{F}$. As the proof size is dependent on the size of the shuffle, ℓ , an interest in the possibility of reducing this parameter arises. The current proposal of curdleproofs only works on shuffles, where the size is a power of 2. The reason is that the underlying proofs, such as the IPA, needs to fold recursively down to 1, by halving the size in every round.

3 RELATED WORK

3.1 Single Secret Leader Election

A Single Secret Leader Election (SSLE) is a protocol where a group of participants randomly elects only one leader from the group. The identity of the leader is kept secret from all other participants so only the leader themselves know that they have been chosen. The elected leader can then later publicly prove that they have been elected [8].

Leading research on SSLE includes proposals for post-quantum secure protocols based on Learning With Errors and Ring Learning With Errors [10]. This work also constructs a new concept called re-randomizable commitment (RRC) for easier work with such protocols. RRC is based on the commit-and-shuffle approach also used in Whisk.

One of the use cases of SSLE is to make Proof of Stake (PoS) blockchains more secure due to the added privacy that the proposer has.

One PoS blockchain that uses an SSLE is Polkadot which uses Saffrole as their SSLE protocol [11]. Saffrole is the production version of the research protocol Sassafras [12]. In this, validators each produce a number of tickets, some of which are winning, depending on some threshold. A Zero-Knowledge Succinct Non-Interactive Argument of Knowledge (ZK-SNARK) is then used to prove that a ticket is winning, after which the winning tickets are published to the chain. A randomization algorithm will then pick, from all the winning tickets, proposers for all the slots two epochs later.

3.2 Shuffling algorithms

The Håstad square shuffle [13] is one of the proposed ways of shuffling, which could be integrated in a shuffling SSLE

such as Whisk. The Håstad square shuffle is a shuffling algorithm that shuffles a vector with n items with a shuffle size of \sqrt{n} . The algorithm works by re-arranging the vector into a $\sqrt{n} \times \sqrt{n}$ square matrix. It then works in time steps, starting at 1. For each odd step, each column and its elements are shuffled independently. For each even step, each row and its elements are shuffled independently as well. Håstad shows that at least three time steps are needed for the shuffle to be secure. The Håstad shuffle is more rigid than the shuffling algorithm used in curdleproofs [14] because of the fixed size of the shuffle being \sqrt{n} .

The Feistel shuffle [15] is a previously used shuffle method in the Whisk protocol [3]. It takes n number of validator trackers and arranges them in a $k \times k$ matrix. Each round the i -th proposer selects the i -th row of the created matrix and shuffles it in the form $F(x, y) = (y, x + y^3 \bmod k)$. The Feistel shuffle was later replaced by the shuffle proposed by Larsen et al. [14]. Ethereum mentioned the reason for this to be that the shuffle by Larsen et al. provides a simpler protocol [3].

3.3 Bulletproofs

A big inspiration for the Curdleproofs protocol is bulletproofs [16]. Bulletproofs is a type of range proof that uses inner product arguments to prove that a committed value is within a certain range without revealing the value itself. Bulletproofs is in itself not a zero-knowledge proof system, but with the help of Fiat Shamir [16] it can be used to create a zero-knowledge proof. Bulletproofs also has had a few iterations and improvements to increase the speed and reduce the size of the proof since it was used in curdleproofs.

One of these is Bulletproofs+ [17] which uses a weighted inner product argument instead of the standard inner product argument to achieve a better performance. Bulletproofs+ is also a zero-knowledge proof by itself unlike the original bulletproofs. Trying to modify Curdleproofs with the weighted inner product argument introduces complications that would need larger modifications and is therefore not suitable. This can be seen in section C

A third version of the Bulletproofs protocol is Bulletproofs++ [18] which uses a new type of argument called the norm argument to achieve a better performance. This comes from the prover only needing to commit to a single vector, rather than two. Therefore, with the two vectors, x and y of a standard IPA, they need to assume $x = y$ for their protocol to work. Then, along with the norm being weighted, which raises the same complications as with Bulletproofs+, this makes it unsuitable for Curdleproofs.

4 APPROACH

As explained in section 2, Curdleproofs makes use of three different proofs. This work focuses on improving the underlying IPA, especially the running time and proof size of the protocol are of interest. The following is our approach to, how we modified the IPA.

4.1 Springproofs

The Springproofs protocol [19] can be used very effectively in solving the problem stated in section 2.3. The theory of

Springproofs provides support for IPAs to use vectors of arbitrary length. Using the findings of Springproofs means Curdleproofs could be used on shuffle sizes other than powers of two. As such, they could lower the shuffle size from the current 128 to a size significantly lower, given it is still secure. Seeing the proof size of Curdleproofs being dependent on ℓ means that this modification would greatly help in lowering it.

One of the most notable findings in Springproofs is the usage of their so-called scheme function. This function is used to ensure that the IPA eventually will fold down to a vector of size 1. In a general IPA, Curdleproofs included, if the size of the vectors were not a power of two, the argument would not recursive down to size 1, as they work by halving the vectors every recursive round.

The core concept of the Springproofs scheme function is to split the vectors into sets, T, S before each recursive round of the protocol. Then, the fold for that round is only done on one of the two sets, T , before the other set, S , is appended again at the end of the recursive round.

Springproofs present different scheme functions and prove some of them to be optimal. One of these optimal functions is an optimized version of their *pre-compression method*, which splits the vectors as seen in Listing 1. The computation is for finding the set, T .

input: n , where $n > 0$

$\{n\} \leftarrow n$

$N \leftarrow 2^{\lceil \log n \rceil - 1}$

$i_h \leftarrow \lfloor (2N - n)/2 \rfloor + 1$

$i_t = \lfloor n/2 \rfloor$

if $n \neq N$:

$\{T\} \leftarrow (i_h : i_t) \cup (N + 1 : n)$

else if $n = N$:

$\{T\} \leftarrow (1 : n)$

$\{S\} \leftarrow \{n\} - \{T\}$

Listing 1: Scheme function f used in CAAUrdleproofs

This can also visually be seen in Figure 1(b), which is figure 1 of the Springproofs paper [19]. In Figure 1(a) is a scheme function which simply pads the vector to the next power of two before running an IPA. If one wanted to run current IPAss on vector that are not a power of two, this would generally be the easiest way to achieve that. Though, this defeats the attempt of lowering the proof size, as it would now correspond to running an IPA on the size of the next power of two.

It is notable to mention that using the folding as shown in Figure 1(b) results in the second recursive round being a size corresponding to a power of two. This means that the rest of the protocol will run as a general IPA, without the actual need for splitting the vectors, which can also be seen in Listing 1.

4.2 CAAUrdleproofs

With the idea from Springproofs in mind, we have made a modification to the IPA of Curdleproofs. We call this modified protocol, CAAUrdleproof. For generality and readability, we show the split of vectors happening every round.

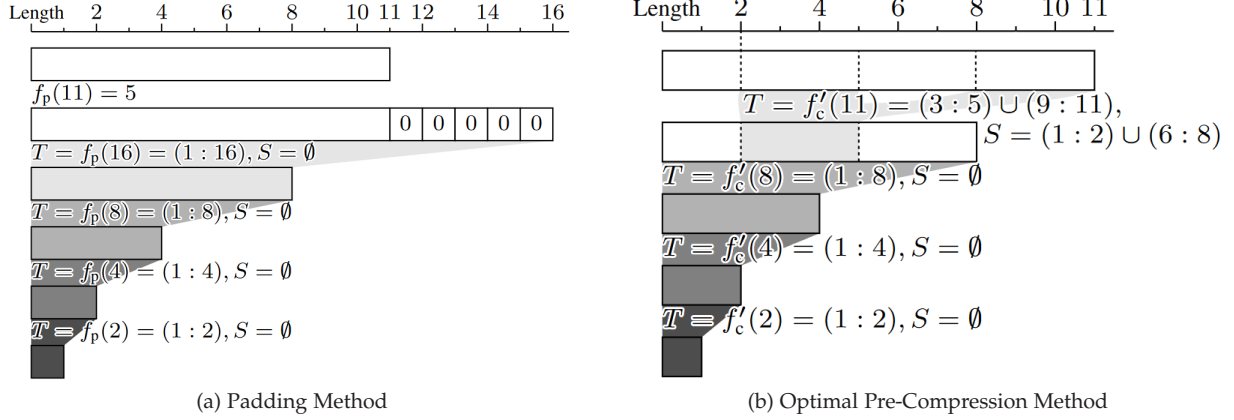


Fig. 1: Folding visualization as seen in the Springproofs paper. Source: [19]

Prover computation

First of all, we have the prover computation, where the proof is constructed. The construction can be seen in Listing 2.

First, we have step 1, which is the setup phase. It is done exactly the same way as in Curdleproofs. In line 2, the prover gets the cryptographic generators, \mathbf{G} , \mathbf{G}' and H , which are going to be used for commitment constructions. To ensure zero-knowledge, two blinding vectors for each commitment are constructed on lines 3–4. These are also given the properties, $(\mathbf{r}_C \times \mathbf{d} + \mathbf{r}_D \times \mathbf{c}) = 0$ and $\mathbf{r}_C \times \mathbf{r}_D = 0$, ensuring the completeness of the protocol.

After this, commitments of the blinding vectors are constructed as B_C and B_D , on lines 5–6. These will eventually be used for verification by the verifier.

From the public input, hash values α, β are then computed on line 7. These are used to ensure the soundness of the protocol.

On lines 8–10, the two vectors are then blinded and multiplied by the α hash to ensure the zero-knowledge and soundness, as well as $H = \beta H$.

Now, the recursive proof construction, and step 2, begins. As explained, at the start of the recursive round, line 13, we find the split of the vectors on line 14, with $f(n)$ being the scheme function from Listing 1. Then on line 15, we find half the length of the T set, as it is on the set, we are doing the recursive folding round on. Equally, on lines 16–19, we split our witness vectors and the group vectors using T and S .

After this, the prover constructs cross-commitment elements on lines 20–23 that are computed on the T set. These are added to the proof on line 24, which eventually is available to the verifier. They are also used to construct a hash value, γ_j , in the next step on line 25.

This value is used on lines 26–29 for completing the folding of $\mathbf{c}, \mathbf{d}, \mathbf{G}, \mathbf{G}'$. We do the fold as in the original Curdleproofs protocol, while also appending the elements of S back onto the vectors. The figure shows a concatenation, but it is important to know that the vectors are appended together as shown in Figure 1(b).

At last, on line 30, n is updated to the length of the concatenated vectors before starting a new round.

	Step 1:	1
	$(\mathbf{G}, \mathbf{G}', H) \leftarrow \text{parse}(crs_{dl_{inner}})$	2
	$\mathbf{r}_C, \mathbf{r}_D \xleftarrow{\$} \mathbb{F}^n$	3
	where $(\mathbf{r}_C \times \mathbf{d} + \mathbf{r}_D \times \mathbf{c}) = 0$ and $\mathbf{r}_C \times \mathbf{r}_D = 0$	4
	$B_C \leftarrow \mathbf{r}_C \times \mathbf{G}$	5
	$B_D \leftarrow \mathbf{r}_D \times \mathbf{G}'$	6
	$\alpha, \beta \leftarrow \text{Hash}(C, D, z, B_C, B_D)$	7
	$\mathbf{c} \leftarrow \mathbf{r}_C + \alpha \mathbf{c}$	8
	$\mathbf{d} \leftarrow \mathbf{r}_D + \alpha \mathbf{d}$	9
	$H \leftarrow \beta H$	10
	Step 2:	11
	$m \leftarrow \lceil \log n \rceil$	12
	while $1 \leq j \leq m$:	13
	$T, S \leftarrow f(n)$	14
	$n \leftarrow \lfloor \frac{ T }{2} \rfloor$	15
	$\mathbf{c} \leftarrow \mathbf{c}_T, \mathbf{c}_S \leftarrow \mathbf{c}_S$	16
	$\mathbf{d} \leftarrow \mathbf{d}_T, \mathbf{d}_S \leftarrow \mathbf{d}_S$	17
	$\mathbf{G} \leftarrow \mathbf{G}_T, \mathbf{G}_S \leftarrow \mathbf{G}_S$	18
	$\mathbf{G}' \leftarrow \mathbf{G}'_T, \mathbf{G}'_S \leftarrow \mathbf{G}'_S$	19
	$L_{C,j} \leftarrow \mathbf{c}_{[n]} \times \mathbf{G}_{[n]} + (\mathbf{c}_{[n]} \times \mathbf{d}_{[n]})H$	20
	$L_{D,j} \leftarrow \mathbf{d}_{[n]} \times \mathbf{G}'_{[n]}$	21
	$R_{C,j} \leftarrow \mathbf{c}_{[n]} \times \mathbf{G}'_{[n]} + (\mathbf{c}_{[n]} \times \mathbf{d}_{[n]})H$	22
	$R_{D,j} \leftarrow \mathbf{d}_{[n]} \times \mathbf{G}_{[n]}$	23
	$\pi_j \leftarrow (L_{C,j}, L_{D,j}, R_{C,j}, R_{D,j})$	24
	$\gamma_j \leftarrow \text{Hash}(\pi_j)$	25
	$\mathbf{c} \leftarrow \mathbf{c}_S \parallel \mathbf{c}_{[n]} + \gamma_j^{-1} \mathbf{c}_{[n]}$	26
	$\mathbf{d} \leftarrow \mathbf{d}_S \parallel \mathbf{d}_{[n]} + \gamma_j \mathbf{d}_{[n]}$	27
	$\mathbf{G} \leftarrow \mathbf{G}_S \parallel \mathbf{G}_{[n]} + \gamma_j \mathbf{G}_{[n]}$	28
	$\mathbf{G}' \leftarrow \mathbf{G}'_S \parallel \mathbf{G}'_{[n]} + \gamma_j^{-1} \mathbf{G}'_{[n]}$	29
	$n \leftarrow \text{len}(c)$	30
	Step 3:	31
	$c \leftarrow c_1$	32
	$d \leftarrow d_1$	33
		34
	return (B_C, B_D, π, c, d)	35

Listing 2: Prover computation for CAAU-IPA in CAAUrdleproofs

The result of this is a proof, π , constructed in $\lceil \log n \rceil$

rounds, but with the proof size being smaller than if the shuffle size was a power of 2.

In step 3, lines 31–35, the folded vectors of size 1 are added to the proof as values as well as the commitments to the blinding values, B_C and B_D . This is what is returned for the verifier to use for verification.

The now constructed proof is then supposed to be added to the block in the chain at the given time slot [3].

Verifier computation

Having the proof on the blockchain allows for each validator to asynchronously verify whether it is a valid proof. Again, the originally proposed verifying protocol has been modified according to Springproofs, which is seen in Listing 3.

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1 Step 1:
2  $(\mathbf{G}, \mathbf{G}', H) \leftarrow \text{parse}(crs_{dl_{inner}})$ 
3  $(C, D, z) \leftarrow \text{parse}(\phi_{dl_{inner}})$ 
4  $(B_C, B_D, \pi, c, d) \leftarrow \text{parse}(\pi_{dl_{inner}})$ 
5  $\alpha, \beta \leftarrow \text{Hash}(C, D, z, B_C, B_D)$ 
6  $H \leftarrow \beta H$ 
7  $C \leftarrow B_C + \alpha C + (\alpha^2 z)H$ 
8  $D \leftarrow B_D + \alpha D$ 
9
10 Step 2:
11  $m \leftarrow \lceil \log n \rceil$ 
12 for  $1 \leq j \leq m$ 
13    $T, S \leftarrow f(n)$ 
14    $n \leftarrow \frac{|T|}{2}$ 
15    $\mathbf{G} = \mathbf{G}_T, \mathbf{G}_S = \mathbf{G}_S$ 
16    $\mathbf{G}' = \mathbf{G}'_T, \mathbf{G}'_S = \mathbf{G}'_T$ 
17    $(L_{C,j}, L_{D,j}, R_{C,j}, R_{D,j}) \leftarrow \text{parse}(\pi_j)$ 
18    $\gamma_j \leftarrow \text{Hash}(\pi_j)$ 
19    $C \leftarrow \gamma_j L_{C,j} + C + \gamma_j^{-1} R_{C,j}$ 
20    $D \leftarrow \gamma_j L_{D,j} + D + \gamma_j^{-1} R_{D,j}$ 
21    $\mathbf{G} \leftarrow \mathbf{G}_S \parallel \mathbf{G}_{[n]} + \gamma_j \mathbf{G}'_{[n]}$ 
22    $\mathbf{G}' \leftarrow \mathbf{G}'_S \parallel \mathbf{G}'_{[n]} + \gamma_j^{-1} \mathbf{G}''_{[n]}$ 
23    $n \leftarrow \text{len}(\mathbf{G})$ 
24
25 Step 3:
26 Check  $C = c \times G_1 + cdH$ 
27 Check  $D = d \times G'_1$ 
28 return 1 if both checks pass, else return 0

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Listing 3: Verifier computation for CAAU-IPA in CAAUrdleproofs

Many of the changes to the verifier protocol are equivalent to the ones made to the prover protocol.

At step 1, the verifier sets up to run the protocol.

The verifier, on line 2, gets the same cryptographic generators used by the prover, \mathbf{G} , \mathbf{G}' and H , from the common reference string. Then, from the public input ϕ , line 3, the verifier gets hold of the original commitments, C and D , as well as the result of the inner product between c and d . From the prover's proof, on line 4, the verifier gets the blinding commitments B_C and B_D , the proof elements π , and the folded vector values c and d . With this, the verifier is able to compute the same α and β challenges as the prover in line 5, as well as computing the same H generator on line 6.

Now the verifier updates the commitments C and D on lines 7–8. The reason being that on lines 7–8 in Listing 2, the witness vectors are updated to be both blinded and multiplied by the challenge, α . Those modifications mean that the commitments C and D need to be commitments to the modified witnesses instead.

The setup phase is now done, and the verifier has to also run a recursive protocol, which is shown in step 2. First, the vectors are on line 13 divided into the two sets, $|T|, |S|$, as in Listing 2. After this, the group vectors are in lines 14–16 split in according to those sets, along with updating n to be half the size of T .

The verifier then, on line 17, retrieves from the proof the cross-product commitment update values for the given round, $L_{C,j}, L_{D,j}, R_{C,j}, R_{D,j}$. These are used for constructing a new commitment, lines 19–20, according to the fold made at round i .

By fetching the cross-commitments of the round, the verifier is able to compute a challenge γ_j , line 18, made from the same public inputs as the prover.

The corresponding left and right side cross-product are then, in lines 19–20, also multiplied by said challenge, γ_j, γ_j^{-1} , respectively. By this time, the C and D commitments are a commitment to the original commitments along with the folded commitment.

\mathbf{G}, \mathbf{G}' are on lines 21–22 updated as in Listing 2 before the protocol on line 23 updates n to be the length of the newly constructed vectors.

As in the prover protocol, this is then repeated for $\lceil \log n \rceil$ rounds, after which the vectors have length 1.

At the end of the protocol, in step 3, the verifier now does its final check. From the prover, line 4, it has retrieved the folded down c and d vectors. It therefore constructs commitments with those elements. So, it constructs $c \times G_1 + cdH$ on line 26, which is the structure of the C commitment as well as $d \times G'_1$ on line 27, which is the structure of the D commitment. The verifier now checks if these commitments match the commitments that were constructed in the recursive part of the protocol. If so, the verifier accepts the proof.

Theorem 1. CAAUrdleproofs is a zero-knowledge argument of knowledge when $|\ell| \geq 8$.

4.3 Shuffle security

The shuffle method proposed by Larsen et al. [14] that was used in Curdleproofs is based on the idea of shuffling a list of proposers over a set of slots. A formal definition of the shuffle is given in Figure 2 [14].

Here the set (c_1, \dots, c_n) is a set of ciphertexts that are shuffled over T slots. In each slot t , a subset of the ciphertexts i_1, \dots, i_ℓ is chosen randomly, shuffled, and added back to the list of ciphertexts. The shuffler then re-encrypts the ciphertexts and publishes them. This process is repeated for T slots and the shuffle is complete. During the T shuffles, some shuffles may be adversarial. This means that whenever the shuffling process is taking place, a part of the shuffles may be adversarial. An adversary can choose to do anything with its shuffle, including not shuffling. Hence, an adversarial shuffle can be seen as no shuffling being done. Therefore, the number of honest shuffles that happen during

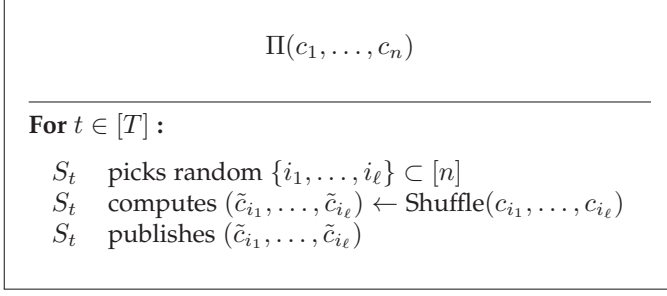


Fig. 2: Distributed shuffling protocol. Source: [14]

the shuffle process is $T_H = T - \beta$, where β is the number of adversarial shuffles.

The adversary can also track cups. For instance, if some of the cups are owned by the adversary. Those tracked cups are denoted by α , which is $\leq n$.

The shuffle is secure if none of the following two events occur. The first event is a short backtracking, where an adversary can find the original ciphertexts from the shuffled ciphertexts. Since the subsets of ciphertexts are chosen randomly in each shuffle, if there are enough adversarial shufflers in a row at the end of the process, then a short backtracking is possible.

The second event that can occur is related to the fact that every shuffle distributes the possibility of a certain ciphertext to be in a certain slot. So, if a shuffle contains a lot of ciphertexts with a larger than average chance of containing a certain ciphertext, then that would imply that there is a higher chance of that ciphertext being in that slot.

It is theoretically possible to find a number of shuffles, given the shuffle size, and a number of adversarial shufflers, to guarantee that the shuffle is secure. For any $0 < \delta < 1/3$, if $T \geq 20n/\ell \ln(n/\delta) + \beta$ and $\ell \geq 256 \ln^2(n/\delta)(1 - \alpha/n)^{-2}$. If T and ℓ are chosen such that the above two conditions are met, then the protocol is an (ϵ, δ) -secure (T, n, ℓ) -shuffle in the presence of a (α, β) -adversary where $\epsilon = 2/(n - \alpha)$.

This formula is the lowest theoretically proven bound for T and ℓ . Plotting numbers relevant to Whisk will show that this theoretical bound is too large to use for argumentation of security. It is, however, possible to find lower secure values for T and ℓ , but this has to be done experimentally.

4.4 Implementation

Implementing the above-explained CAAUrdleproofs protocol introduced some optimizations required to have the code run as fast as possible. These are explained in the following with a focus on how CAAUrdleproofs differentiates itself from Curdleproofs. Both our implementation of CAAUrdleproofs and the experiment involving the security of the shuffle are publicly available on GitHub¹. The implementation of CAAUrdleproofs is a fork of and builds directly on the already existing Curdleproofs code.

4.4.1 CAAUrdleproofs

The protocol in Curdleproofs [2] introduces a lot of multiscalar multiplications. As such, CAAUrdleproofs also in-

roduces these multiplications. This allows for checking calculations of the form:

$$C \stackrel{?}{=} \mathbf{x} \times (\mathbf{g} \parallel \mathbf{h} \parallel G_T \parallel G_U \parallel H \parallel \mathbf{R} \parallel \mathbf{S} \parallel \mathbf{T} \parallel \mathbf{U}) \quad (1)$$

As explained by Curdleproofs, the verifier computation can be significantly optimized by checking the multiscalar multiplications as a single check at the end of the protocol instead.

CAAUrdleproofs introduced a slight difference on this topic in regard to the IPAs, SamePerm and SameMSM. In each recursive round, both the folded vectors and the commitments are being multiplied by verification scalars, γ_j . To keep track of which elements of the vectors are multiplied by each γ_j , a function called `get_verification_scalars_bitstring` is used. The output of this function is a list of length ℓ , each element with a list corresponding to the rounds in which γ_j was multiplied to the element. Curdleproofs' implementation is simpler than CAAUrdleproofs' in this case. As Curdleproofs works on powers of two, it is always the right half of the vectors in each round that are multiplied by the challenge.

The multiplication of challenges are not as easily trackable in the CAAUrdleproofs protocol. Here, it is necessary to simulate a run though the recursive protocol. Though, this should not have a big impact on performance, as it is run over vectors of small integers, and never actually has to do any multiplications. It is simply used as a measuring tool.

The protocol used in the implementation can be seen in Listing 4. A list, `ActivePos`, on line 32, keeps track of the original index placement and its position after each fold. Doing this, we can run the recursion and find the correct challenges for each index, while still knowing what the original index was. A bit matrix, $b_{i,j}$, is constructed as in Curdleproofs, such that the vector, \mathbf{s} , is made in the same way for both protocols.

The vector, \mathbf{u} , seen on line 3, is used for optimization in the grand product argument rather than \mathbf{G}' , and the `AccumulateCheck` function, on line 21 and 23, is used for the multiscalar multiplication optimization. For a thorough explanation of these, we refer to Curdleproofs [2].

In Curdleproofs, both the SamePerm and SameMSM proof are recursive IPAs. So, the modifications and optimization used on the SamePerm argument are also used on the SameMSM argument. This includes the split into set T and S before recursion, and the construction of the bit matrix, $b_{i,j}$, to keep track of multiplications on individual elements.

4.4.2 Shuffle Security

As mentioned in section 4.3, the theoretically proven bound, on the necessary number of shuffles to ensure security is too high. Hence, as also done in [14], we implement an experiment to find the bounds, where the shuffle is secure. The goal of the experimental code is to find the number of honest shuffles required for security.

We inherit the authors of the shuffle's terminology, and interpret each ciphertext as a cup that can contain water. Each cup contains an amount of water between 0 and 1.

An experiment run starts with the first cup being full and the rest being empty. As mentioned, α cups are tracked by an adversary, the first $n - \alpha$ cups are called active cups,

1. <https://github.com/AAU-Dat/curdleproofsplus/tree/SIPA>

```

1 Step 1:
2  $(\mathbf{G}, H) \leftarrow \text{parse}(crs_{dl_{inner}})$ 
3  $(C, D, z, \mathbf{u}) \leftarrow \text{parse}(\phi_{dl_{inner}})$ 
4  $(B_C, B_D, \pi, c, d) \leftarrow \text{parse}(\pi_{dl_{inner}})$ 
5  $\alpha, \beta \leftarrow \text{Hash}(C, D, z, B_C, B_D)$ 
6
7 Step 2:
8  $m \leftarrow \lceil \log n \rceil$ 
9 for  $1 \leq j \leq m$ 
10    $T, S \leftarrow f(n)$ 
11    $n \leftarrow \frac{|T|}{2}$ 
12    $(L_{C,j}, L_{D,j}, R_{C,j}, R_{D,j}) \leftarrow \text{parse}(\pi_j)$ 
13    $\gamma_j \leftarrow \text{Hash}(\pi_j)$ 
14    $n \leftarrow n + \text{len}(S)$ 
15
16 Step 3:
17 CP:  $\gamma \leftarrow (\gamma_m, \dots, \gamma_1)$ 
18 CAAUP:  $\gamma \leftarrow (\gamma_1, \dots, \gamma_m)$ 
19 Compute s: see below for difference
20
21  $\text{AccumulateCheck}(\gamma \times \mathbf{L}_C + (B_C + \alpha C + (\alpha^2 z)H)$ 
22    $+ \gamma^{-1} \times \mathbf{R}_C \stackrel{?}{=} (cs \| cd\beta) \times (\mathbf{G} \| H))$ 
23  $\text{AccumulateCheck}(\gamma \times \mathbf{L}_D + (B_D + \alpha D)$ 
24    $+ \gamma^{-1} \times \mathbf{R}_D \stackrel{?}{=} d(s' \circ \mathbf{u}) \times \mathbf{G})$ 
25 return 1
26
27 s-step Curdleproofs:
28 for  $1 \leq j \leq n$ :
29    $s_i = \sum_{j=1}^m \delta_j^{b_{i,j}}, b_{i,j} \in \{0, 1\} \text{ s.t. } i = \sum_{j=1}^m b_{i,j} 2^j$ 
30    $s'_i = \sum_{j=1}^m \delta_j^{-b_{i,j}}$ 
31 s-step CAAUrdleproofs:
32  $\text{ActivePos} \leftarrow [(i, i), i = 1, \dots, n]$ 
33 for  $1 \leq j \leq m$ :
34    $h \leftarrow \frac{2^{\lceil \log n \rceil}}{2}$ 
35    $f \leftarrow n - h$ 
36    $nf \leftarrow h - f$ 
37    $fs \leftarrow \frac{nf}{2}$ 
38   for  $(i, k) \text{ in } \text{ActivePos}$ :
39     if  $k \geq h$ :
40        $b_{i,j} \leftarrow 1$ 
41        $\text{newPos} = k - h - fs$ 
42     else:
43        $b_{i,j} \leftarrow 0$ 
44        $\text{newPos} = k$ 
45      $\text{nextActivePos.push}((i, \text{newPos}))$ 
46    $\text{ActivePos} \leftarrow \text{nextActivePos}$ 
47    $n \leftarrow h$ 
48 for  $1 \leq j \leq n$ :
49    $s_i = \sum_{j=1}^m \delta_j^{b_{i,j}}$ 
50    $s'_i = \sum_{j=1}^m \delta_j^{-b_{i,j}}$ 

```

Listing 4: Optimized verifier computation for CAAU-IPA in CAAUrdleproofs

while the last α cups are tracked. So, at each shuffle, the shuffler randomly picks ℓ ciphertexts and shuffles them, also randomly. Meanwhile, an average of the water between the

active indices of the ℓ -shuffle is found. All active indices are given this amount of water.

Now, after each shuffle, if any cup has more than $2/(n - \alpha)$ water, its position can be predicted by the adversary, hence the shuffle is insecure [14]. If a position can be predicted, another round of shuffling is performed. This method is used until no cup exceeds the threshold, after which the shuffle is deemed secure.

The experiment denotes how many rounds it took before the shuffle was secure.

By repeating this experiment for several runs, one can experimentally say, when a shuffle with given parameters is secure.

5 EXPERIMENTAL PROTOCOL

In this section, we will describe how our experiments are run, and what we want to measure. We also discuss which parameters we can tweak in the different experiments that we have.

The experiments are run on a virtual machine hosted on Strato CLAAUDIA through Aalborg University. The machine is using an Intel Xeon Cascadelake processor, CPU family 6, model 85. It has 16 virtual CPUs and 64 GB of RAM available. The virtual machine is running Ubuntu Server 24.

5.1 CAAUrdleproof

In this experiment we measure the time to run the CAAUrdleproofs protocol. The results will be compared to those of Curdleproofs, which we re-run on our own hardware. As Curdleproofs already has a Rust benchmark implemented, we will be using that same benchmark for both protocols. The parameter that we want to change between benchmark runs is the shuffle size, ℓ .

In CAAUrdleproofs, we will test the protocol with $\ell = \{8, 9, \dots, 256\}$.

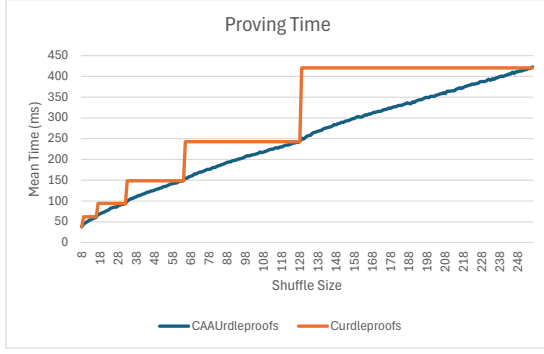
Since Curdleproofs is unable to run benchmarks, unless the shuffle size is a power of two, those benchmarks will be run on values $\ell = \{8, 16, 32, 64, 128, 256\}$.

5.2 Shuffle security

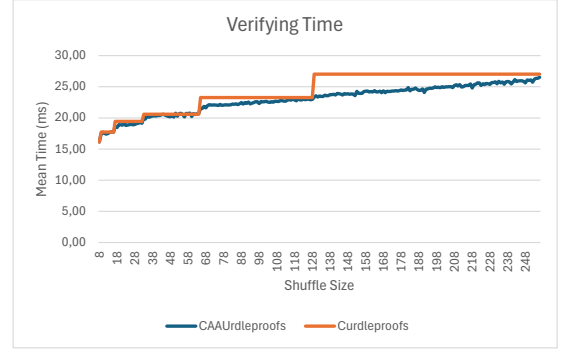
In this experiment we run the shuffle protocol with varying shuffle sizes and varying number of adversarial tracked ciphertexts. The purpose of this experiment is to find the lowest possible shuffle size that is still secure. We therefore run the experiment with shuffle sizes, ℓ , between 64 and 128. For the number of adversarial tracked ciphertexts, we use the values $\alpha = \{1/2, 1/3, 1/4\}$

Because Curdleproofs is meant to be used in an Ethereum setting, all the experiments were done with a maximum of 8192 shuffles. Also, the experiments shuffle over a set of 16,384 ciphertexts. Both of these numbers come from the Ethereum Whisk proposal [3].

Every experiment is run 1000 times to avoid statistical uncertainty. As done by the shuffle authors [14], we will denote the 20th, 40th, 60th, 80th, and 100th percentile on when the shuffle is deemed secure by the experimental runs.



(a) Proving Time



(b) Verifying Time

Fig. 3: The timed results compared between CAAUrdleProofs and Curdleproofs

6 RESULTS

6.1 Proving and Verifying Times

After running the experiment where Curdleproofs and CAAUrdleproofs were compared across different shuffle sizes, we obtained the results shown in Figure 3.

As mentioned in section 5.1, CAAUrdleproofs was run with a shuffle size ℓ of $\{8, 9, \dots, 256\}$ but Curdleproofs was only run with a shuffle size ℓ of $\{8, 16, 32, 64, 128, 256\}$. This is why the results for Curdleproofs show the shuffle size, ℓ , instantly goes up to the next power of 2, because it theoretically would have to pad the input set until it reached the next power of 2.

From the results, we can see that CAAUrdleproofs and Curdleproofs have similar proving and verifying times when ℓ is a power of 2. However, when ℓ is not a power of 2, CAAUrdleproofs is faster.

The results for the verifying time also shows that the verifying time jumps up the first four times it reaches a power of 2.

Additional to the proving and verifying times, the time used on shuffling is also lower for any ℓ that is not a power of 2. Though, that was to be expected since CAAUrdleproofs uses the same shuffling algorithm as Curdleproofs but does not have to add additional padding values to the non power of 2 input sizes.

6.2 Shuffle security

The results of the shuffle security experiment are shown in Figure 4.

Figure 4 shows the mean of the 1000 runs of each shuffle size ℓ as well as one standard deviation higher and lower.

We can see that the bigger the shuffle size ℓ is, the less honest shuffles are necessary to make the shuffle secure. We also see that the bigger the shuffle size the narrower the standard deviation gets.

From the results of the experiment with $\alpha = 8192$ we can see that number of honest shuffles necessary to make the shuffle secure sharply goes down until a size of $\ell = 64$, and then it starts to flatten out. we can see that with a size of $\ell = 75$ we need about 1/3 of the shuffles to be honest to

make the shuffle secure. Likewise, we can see the at $\ell = 108$ we need about 1/4 of the shuffles to be honest to make the shuffle secure.

In general all three of the experiments, despite the difference in α , show the same trend. They all level out but the higher the α is, the lower the leveling happens but the later it happens as well. There are two things however that are different between the experiments. At an α of 4096 we can see that at the start, with $\ell = 32$, the mean number of honest shuffles necessary to make the shuffle secure is ~ 500 lower than the 2 others. As ℓ increases, the mean number of honest shuffles necessary to make the shuffle secure becomes similar to the other α values. Another thing that differs between the experiments is that they all have sudden dip later on in the experiment. Here we can see a trend that the lower the α is, the earlier the dip happens.

7 DISCUSSION

This is the discussion

8 CONCLUSION

This is the conclusion

9 FUTURE WORK

This is the future work.

10 ACKNOWLEDGEMENTS

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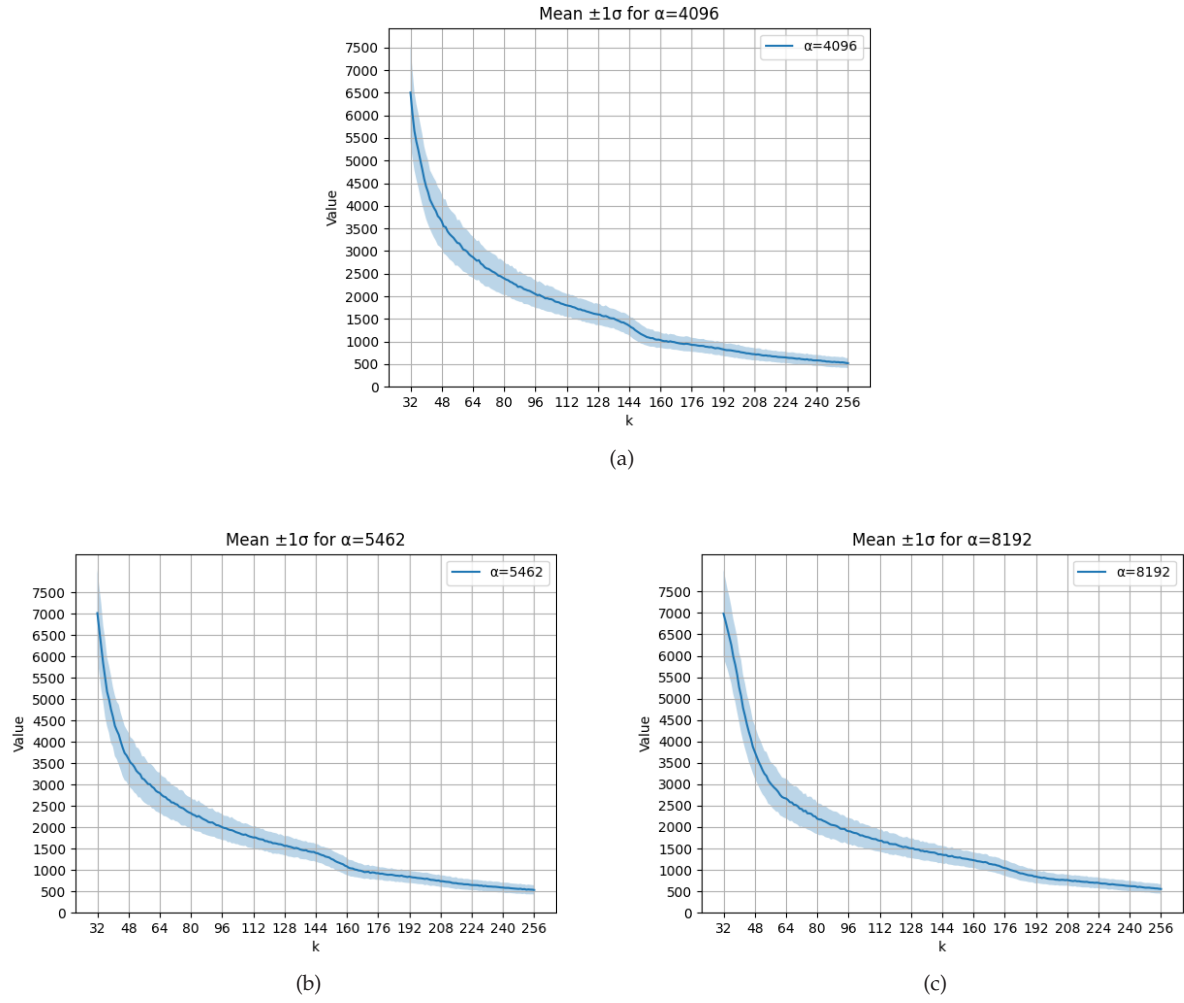


Fig. 4: The results of the shuffle security experiment showing the mean amount of honest shuffles necessary with one standard deviation

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APPENDIX A

DEFINITIONS OF ZERO-KNOWLEDGE ARGUMENT OF KNOWLEDGE

Definition 3 (Honest-Verifier Zero-Knowledge). *An interactive argument $(Setup, P, V)$ for a relation R is honest-verifier zero-knowledge, if there exists a probabilistic polynomial time simulator, such that there exists a negligible function $\epsilon(\lambda)$, for all adversaries A_1 and A_2*

$$\left| \Pr \left[\begin{array}{l} (x, w) \in \mathcal{R} \wedge \\ \mathcal{A}_1(tr) = 1 \end{array} \middle| \begin{array}{l} \sigma \leftarrow Setup(1^\lambda) \\ (x, w, \rho) \leftarrow \mathcal{A}_2(\sigma) \\ tr \leftarrow SIM(x, \rho) \end{array} \right] - \Pr \left[\begin{array}{l} (x, w) \in \mathcal{R} \wedge \\ \mathcal{A}_1(tr) = 1 \end{array} \middle| \begin{array}{l} \sigma \leftarrow Setup(1^\lambda) \\ (x, w, \rho) \leftarrow \mathcal{A}_2(\sigma) \\ tr \leftarrow \langle \mathcal{P}(\sigma, x, w), \mathcal{V}_\rho(\sigma, x) \rangle \end{array} \right] \right| \leq \epsilon(\lambda)$$

Definition 4 (Non-Interactive Knowledge-Soundness). A non-interactive random oracle argument $(Setup, P, V)$ for relation R is knowledge sound, if there exists an efficient knowledge extractor \mathcal{E} and a positive polynomial z , such that for any statement $x \in \{0, 1\}^\lambda$ and prover P^* with at most Q queries to the random oracle RO ,

$$\Pr \left[(x, w') \in R \mid \begin{array}{l} \sigma \leftarrow Setup(1^\lambda) \\ w' \leftarrow \mathcal{E}^{P^*}(x) \end{array} \right] \geq \frac{\epsilon(P^*, x) - \kappa(|x|, Q)}{z(|x|)},$$

Definition 5 (Completeness). An argument $(Setup, P, V)$ is complete, if for any statement $x \in L$ and witness w such that $(x, w) \in R$, there exists a negligible function $\mu(\lambda)$, such that

$$\Pr \left[\langle P(\sigma, x, w), V(\sigma, x) \rangle = 1 \mid \sigma \leftarrow Setup(1^\lambda) \right] \geq 1 - \mu(\lambda)$$

APPENDIX B PROOF OF THEOREM 1

Proof. The following proof is divided into two separate proofs. First we prove HVZK.

After this, both knowledge-soundness and completeness are proven in the same proof.

Proof of HVZK: CAAUrdleproofs is the Curdleproofs DL IPA on which the Springproofs protocol has been applied. So to help show that it is HVZK, we refer to Theorem 5 of Springproofs [19].

Theorem 2 (Springproofs Theorem 5). Suppose IPA_k is a HVZK IPA which reduces a relation $R_{z,k}$ into a relation $R_{z,k/2}$, and the blinding factors in the two relations distribute independently. Given a scheme function f , if the $SIPA_{IPA}(f)$ is terminative for any lengths n of the witness vector, and there exists a polynomial $\text{poly}(\lambda)$ such that the number of rounds $m < \text{poly}(\lambda)$, then $SIPA_{IPA}(f)$ is HVZK when $n \geq 2$.

Given this Theorem, we interpret IPA_k as the Curdleproofs DL IPA.

In Theorem 5.3.1 of the Curdleproofs paper, they prove their IPA to be zero-knowledge [2]. They do this by help of a simulator and show that the prover's and simulator's response are distributed identically. This matches the definition of HVZK from Definition 2, hence the Curdleproofs IPA is HVZK.

We also know that the IPA is a folding argument, which reduces the size of the argument by half after each iteration. In this reduction, Curdleproofs also proved in Theorem 5.3.1 that the values $B_C, B_D, L_{C,j}, L_{D,j}, R_{C,j}, R_{D,j}$ are blinded and identically distributed.

The scheme function used in CAAUrdleproofs, as seen in Figure 1(b), is shown by Springproofs to be a variant of their pre-compression method [19]. Springproofs show this function to be optimal in the number of folding steps, hence it must also terminate. Specifically, the pre-compression is shown to run in $\lceil \log n \rceil$ folding rounds, satisfying the existence of the polynomial mentioned in Theorem 5.

Curdleproofs show their argument to be zero-knowledge in the random oracle model provided $|G| \geq 8$ [2]. Therefore, following Theorem 1, CAAUrdleproofs must be HVZK when $n \geq 8$.

Proof of knowledge-soundness and completeness:

For soundness and completeness, we refer to Theorem 3 of Springproofs [19].

Theorem 3 (Springproofs Theorem 3). Given a terminative $SIPA(f)$, if the number of compression steps in $SIPA(f)$ is $O(\log n)$, then $SIPA(f)$ is a complete and computational knowledge sound argument of relation (1). Moreover, the Fiat-Shamir transformation of $SIPA(f)$ is a non-interactive random oracle argument having completeness and computational knowledge soundness as well.

Here, relation (1) is

$$\{(g, h \in \mathbb{G}^n, u, P \in \mathbb{G}; a, b \in \mathbb{F}_p^n) : P = g^a h^b u^{\langle a, b \rangle}\} \quad (2)$$

or analogously for an additive cryptographic group:

$$\{(g, h \in \mathbb{G}^n, u, P \in \mathbb{G}; a, b \in \mathbb{F}_p^n) : \quad (3)$$

$$P = a \times g + b \times h + \langle a, b \rangle u\} \quad (4)$$

Relating that to Curdleproofs, they mention that they discuss the IPA for the relation

$$\left\{ (C, D, z; c, d) \mid \begin{array}{l} C = c \times G, \\ D = d \times G', \\ z = c \times d \end{array} \right\} \quad (5)$$

Though, taking inspiration from Bulletproofs, which also happens to be the IPA used in Springproofs, they include a commitment to the inner product, z , in commitment C [16]. So, before the addition of blinding values and challenges, the relation they want to prove is:

$$\left\{ \left(\begin{array}{l} G, G' \in \mathbb{G}^n, \\ C, D \in \mathbb{G}, \\ z \in \mathbb{F}_p \end{array} \mid \begin{array}{l} c, d \in \mathbb{F}_p^n \end{array} \right) \mid \begin{array}{l} C = c \times G + zH, \\ D = d \times G', \\ z = c \times d \end{array} \right\} \quad (6)$$

We can now take a look at Springproofs' P commitment in relation to Curdleproofs' C and D commitments. If we add together Curdleproofs' two commitment, we get:

$$C + D = c \times G + d \times G' + zH \quad (7)$$

This exactly the same commitment as in Equation 4.

Therefore, using Curdleproofs' DL IPA and the pre-compression scheme function, we can instantiate $SIPA(f)$, equivalent to CAAUrdleproofs, as a terminative $SIPA(f)$, with $O(\log n)$ compression steps. Hence, $SIPA(f)$ is a complete and computational knowledge sound argument of relation (1). We have just shown that Curdleproofs' IPA proves the same relation, so the properties hold for our $SIPA(f)$ as well. Furthermore, Curdleproofs uses the Fiat-Shamir transformation for its verifier challenges. So, the $SIPA(f)$, analogously CAAUrdleproofs, is a non-interactive random oracle argument having completeness and computational knowledge soundness as well.

From this, we can conclude that CAAUrdleproofs is a zero-knowledge argument of knowledge when shuffle size $|\ell| \geq 8$. \square

APPENDIX C CURDLEPROOFS WEIGHTED INNER PRODUCT ARGUMENT MODIFICATION ATTEMPT